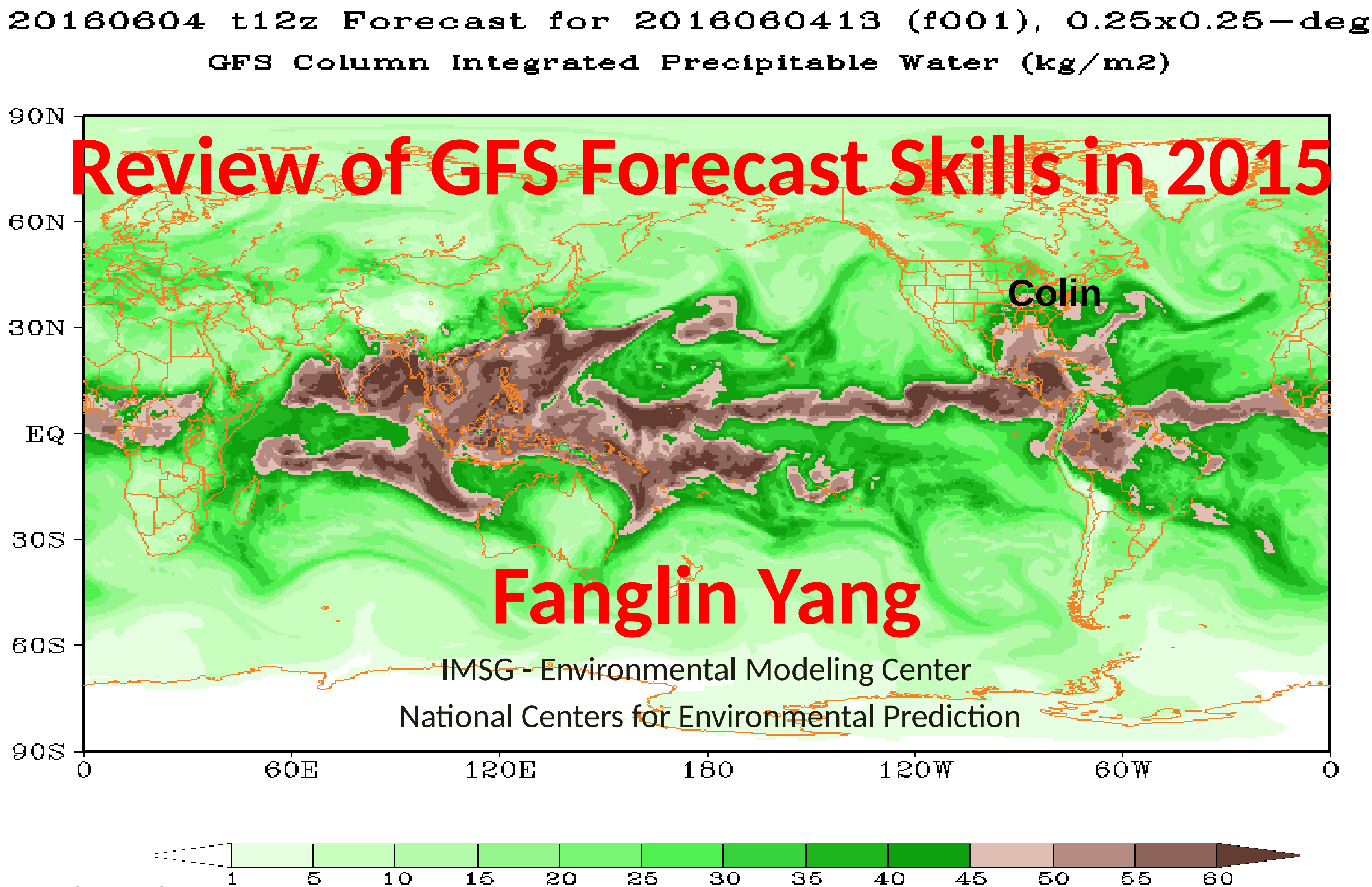
Review of GFS Forecast Skills in 2015



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Acknowledgments : All NCEP EMC Global Climate and Weather Modeling Branch members are acknowledged for their contributions to the development and application of the Global Forecast Systems. **Disclaimer**: The review does not cover all aspects of the complex system, and is biased towards the presenter's personal experience.

Change History of GFS Configurations

Mon/Year	Levels	Truncations	Z-cor/dyncore	Major components upgrade
Aug 1980	12	R30 (375km)	Sigma Eulerian	first global spectral model, rhomboidal
Oct 1983	12	R40 (300km)	Sigma Eulerian	
Apr 1985	18	R40 (300km)	Sigma Eulerian	GFDL Physics
Aug 1987	18	T80 (150km)	Sigma Eulerian	First triangular truncation; diurnal cycle
Mar 1991	18	T126 (105km)	Sigma Eulerian	
Aug 1993	28	T126 (105km)	Sigma Eulerian	Arakawa-Schubert convection
Jun 1998	42	T170 (80km)	Sigma Eulerian	Prognostic ozone; SW from GFDL to NASA
Oct 1998	28	T170 (80km)	Sigma Eulerian	the restoration
Jan 2000	42	T170 (80km)	Sigma Eulerian	first on IBM
Oct 2002	64	T254 (55km)	Sigma Eulerian	RRTM LW;
May 2005	64	T382 (35km)	Sigma Eulerian	2L OSU to 4L NOAH LSM; high-res to 180hr
May 2007	64	T382 (35km)	Hybrid Eulerian	SSI to GSI
Jul 2010	64	T574 (23km)	Hybrid Eulerian	RRTM SW; New shallow cnvtion; TVD tracer
Jan 2015	64	T1534 (13km)	Hybrid Semi-Lag	SLG; Hybrid EDMF; McICA etc
May2016	64	T1534 (13km)	Hybrid Semi-Lag	4-D Hybrid En-Var DA

Vertical layers double every ~11 yrs; change of horizontal resolution is rapid (~30 times in 35 years); sigma-Eulerian used for 27 yrs

Source http://www.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html

Major GFS Changes

- 3/1999
  - **AMSU-A** and HIRS-3 data
- 2/2000
  - **Resolution change: T126L28 □ T170L42   (100 km □ 70 km)**
  - Next changes
    - 7/2000 (hurricane relocation)
    - 8/2000 (data cutoff for 06 and 18 UTC)
    - 10/2000 – package of minor changes
    - 2/2001 – radiance and moisture analysis changes
- 5/2001
  - **Major physics upgrade (prognostic cloud water, cumulus momentum transport)**
  - Improved QC for AMSU radiances
  - Next changes
    - 6/2001 – vegetation fraction
    - 7/2001 – SST satellite data
    - 8/200 – sea ice mask, gravity wave drag adjustment, random cloud tops, land surface evaporation, cloud microphysics…)
    - 10/ 2001 – snow depth from model background
    - 1/2002 – Quikscat included

Major GFS Changes (cont'd)

- 11/2002
  - **Resolution change: T170L42 → T254L64 (70 km → 55 km)**
  - Recomputed background error
  - Divergence tendency constraint in tropics turned off
  - Next changes
    - 3/2003 – NOAA-17 radiances, NOAA-16 AMSU restored, Quikscat 0.5 degree data
    - 8/2003 – RRTM longwave and trace gases
    - 10/2003 – NOAA-17 AMSU-A turned off
    - 11/2003 – Minor analysis changes
    - 2/2004 – mountain blocking added
    - 5/2004 – NOAA-16 HIRS turned off
- 5/2005
  - **Resolution change: T254L64 → T382L64 (55 km → 38 km)**
  - **2-L OSU LSM → 4-L NOHA LSM**
  - Reduce background vertical diffusion
  - Retune mountain blocking
  - Next changes
    - 6/2005 – Increase vegetation canopy resistance
    - 7/2005 – Correct temperature error near top of model

Major GFS Changes (cont'd)

- 8/2006
  - Revised orography and land-sea mask
  - NRL ozone physics
  - Upgrade snow analysis
- 5/2007
  - **SSI (Spectral Statistical Interpolation) → GSI (Gridpoint Statistical Interpolation).**
  - **Vertical coordinate changed from sigma to hybrid sigma-pressure**
  - New observations (COSMIC, full resolution AIRS, METOP HIRS, AMSU-A and MHS)
- 12/2007
  - JMA high resolution winds and SBUV-8 ozone observations added
- 2/2009
  - **Flow-dependent weighting of background error variances**
  - **Variational Quality Control**
  - METOP IASI observations added
  - Updated Community Radiative Transfer Model coefficients
- 7/2010
  - **Resolution Change: T382L64 → T574L64 (38 km → 23 km)**
  - **Major radiation package upgrade (RRTM2 , aerosol, surface albedo etc)**
  - **New mass flux shallow convection scheme; revised deep convection and PBL scheme**
  - **Positive-definite tracer transport scheme to remove negative water vapor**

Major GFS Changes (cont'd)

- 05/09/2011
  - **GSI**: Improved OMI QC; Retune SBUV/2 ozone ob errors; Relax AMSU-A Channel 5 QC; New version of CRTM 2.0.2 ; Inclusion of GPS RO data from SAC-C, C/NOFS and TerraSAR-X satellites; Inclusion of uniform (higher resolution) thinning for satellite radiances ; Improved GSI code with optimization and additional options; Recomputed background errors; Inclusion of SBUV and MHS from NOAA-19 and removal of AMSU-A NOAA-15 .
  - **GFS:** New Thermal Roughness Length -- Reduced land surface skin temperature cold bias and low level summer warm bias over arid land areas; Reduce background diffusion in the Stratosphere .

- 5/22/2012
  - **GSI Hybrid EnKF-3DVAR** : A hybrid variational ensemble assimilation system is employed. The background error used to project the information in the observations into the analysis is created by a combination of a static background error (as in the prior system) and a new background error produced from a lower resolution (T254) Ensemble Kalman Filter.
  - **Other GSI Changes:** Use GPS RO bending angle rather than refractivity; Include compressibility factors for atmosphere ; Retune SBUV ob errors, fix bug at top ; Update radiance usage flags; Add NPP ATMS satellite data, GOES-13/15 radiance data, and SEVERI CSBT radiance product ; Include satellite monitoring statistics code in operations ; Add new satellite wind data and quality control.

- 09/05/2012
  - **GFS** : A look-up table used in the land surface scheme to control Minimum Canopy Resistance and Root Depth Number was updated to reduce excessive evaporation. This update was aimed to mitigate GFS cold and moist biases found in the late afternoon over the central United States when drought conditions existed in summer of 2012.

Major GFS Changes (cont'd)

- **07-08/2013**
  - GFS was moved from IBM CCS to WCOSS supercomputers. They two systems have different architectures.
  - GSI change on August 20: New satellite data, including METOP-B, SEVIRI data from Meteosat-10, and NPP CrIS data.

- **01/14/2015**
  - **Upgrade to T1534 Semi-Lagrangian (~13km)** : Use Lagrangian instead Hermite vertical interpolation; Use high resolution daily RGT SST and daily sea ice analysis; Extend high resolution forecast from 8 days to 10 days; Use McICA radiation approximation; Reduced drag coefficient at high wind speeds; Hybrid EDMF PBL scheme and TKE dissipative heating; Retuned ice and water cloud conversion rates, background diffusion of momentum and heat, orographic gravity-wave forcing and mountain block; Updated physics restart and sigio library; Consistent diagnosis of snow accumulation in post and model; Compute and output frozen precipitation fraction; Divergence damping in the stratosphere to reduce noise; Added a tracer fixer for maintaining global column ozone mass; Stationary convective gravity wave drag; New blended snow analysis to reduce reliance on AFWA snow; Changes to treatment of lake ice to remove unfrozen lake in winter; Modified initialization to reduce a sharp decrease in cloud water in the first model time step; Replace Bucket soil moisture climatology with CFS/GLDAS; Add vegetation dependence to the ratio of the thermal and momentum roughness.
  - **GSI Changes**: increase horizontal resolution of ensemble from T254 to T574;   reduce number of second outer loop iterations from 150 to 100; upgrade to CRTM v2.1.3 ; move to enhanced radiance bias correction scheme; correct bug in AMSU-A cloud liquid water bias correction term; assimilate new radiances: F17 an F18 SSMIS, MetOp-B IASI ; increase ATMS observation errors; turn on cloud detection channels for monitored instruments: NOAA-17, -19 HIRS, GOES-13 and -14 sounders; changes in assimilation of atmospheric motion vectors (AMV): assimilate NESDIS GOES hourly AMVs, improve AMV quality control ; improve GPS RO quality control .

Major GFS Changes (cont'd)

- **05/11/2016**

  - **Data Assimilation Upgrade**

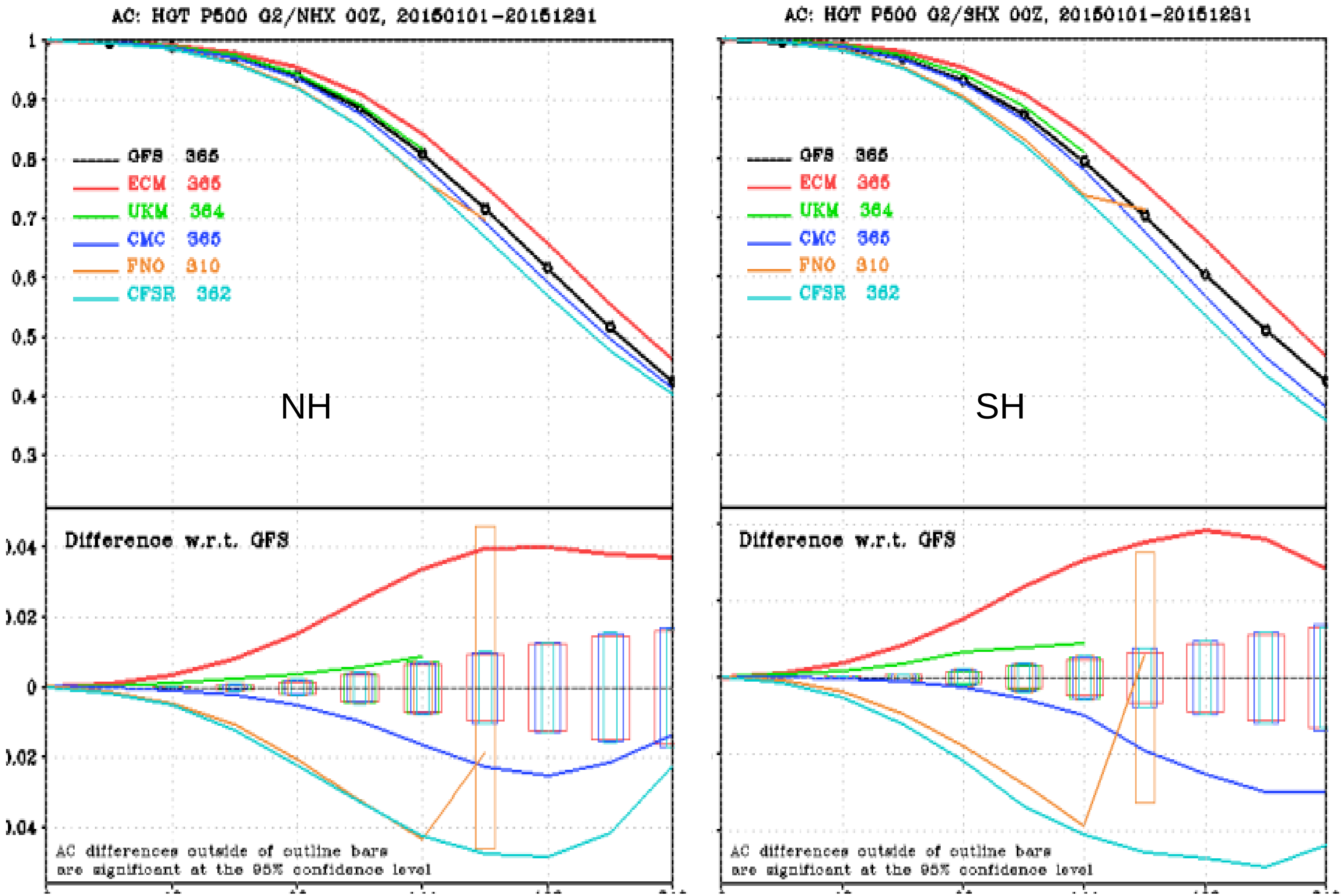
    * Upgrade the 3D Hybrid Ensemble-Variational to **4D Hybrid Ensemble-Variational Data Assimilation**.
    * **Multivariate Ozone update**
    * Assimilate **all-sky** (clear and cloudy) **radiances**
    * Bias correct aircraft data
    * Modify relocation and storm tracking to allow hourly tropical cyclone relocation
    * other upgrades (e.g. CRTM, Data selection/thinning, AMV winds, etc.)

  -Model Upgrade

    * Corrections to land surface to reduce summertime warm, dry bias over Great Plains
    * Hourly output fields through 120-hr forecasts
    * add five more levels from 10 hPa to 1 hPa in post-processed pgb files

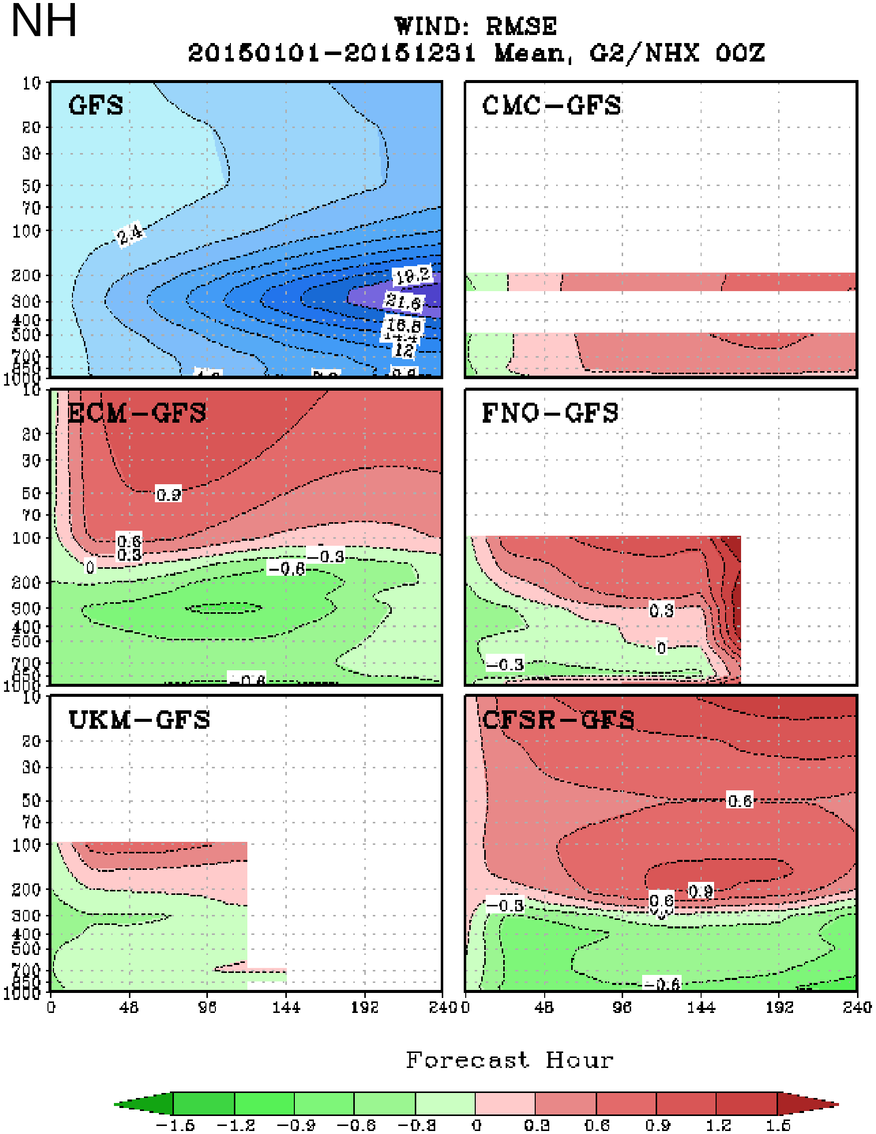
2015 Performance Stats

2005 Annual Mean 500-hPa HGT AC

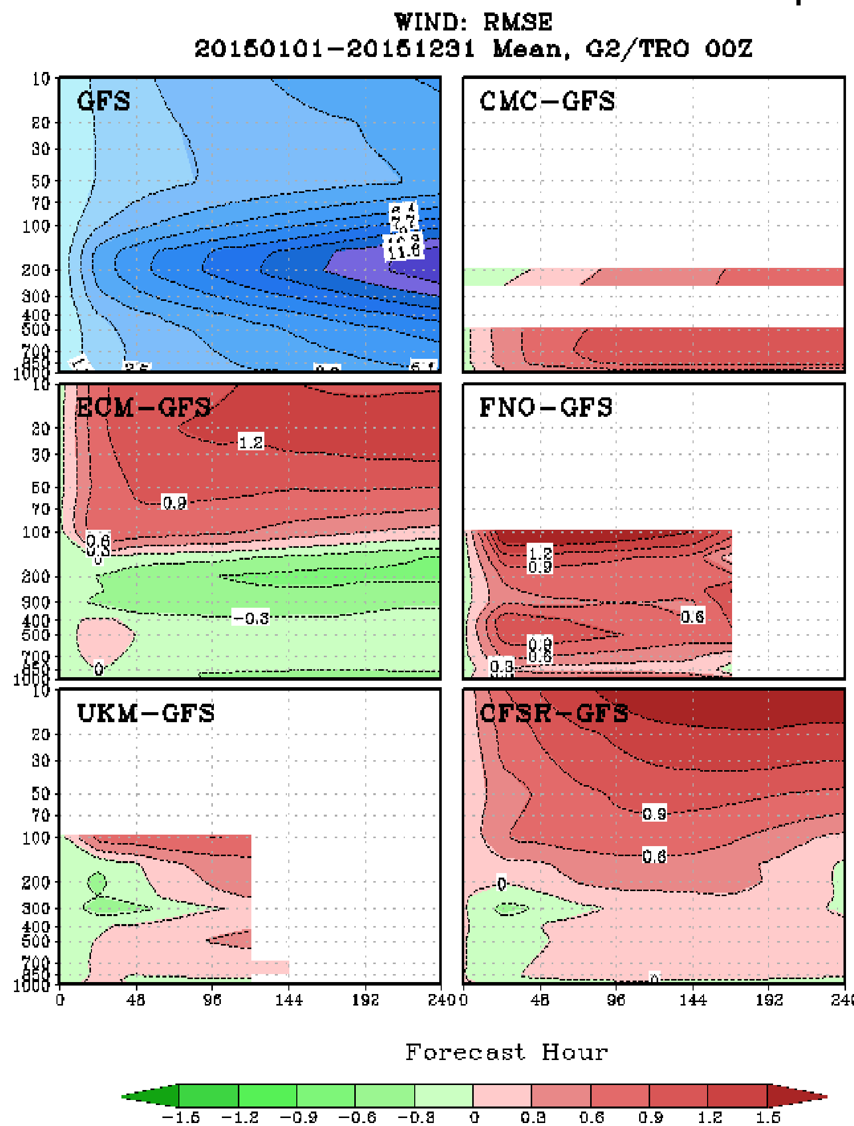


2005 Annual Mean Wind RMSE

NH

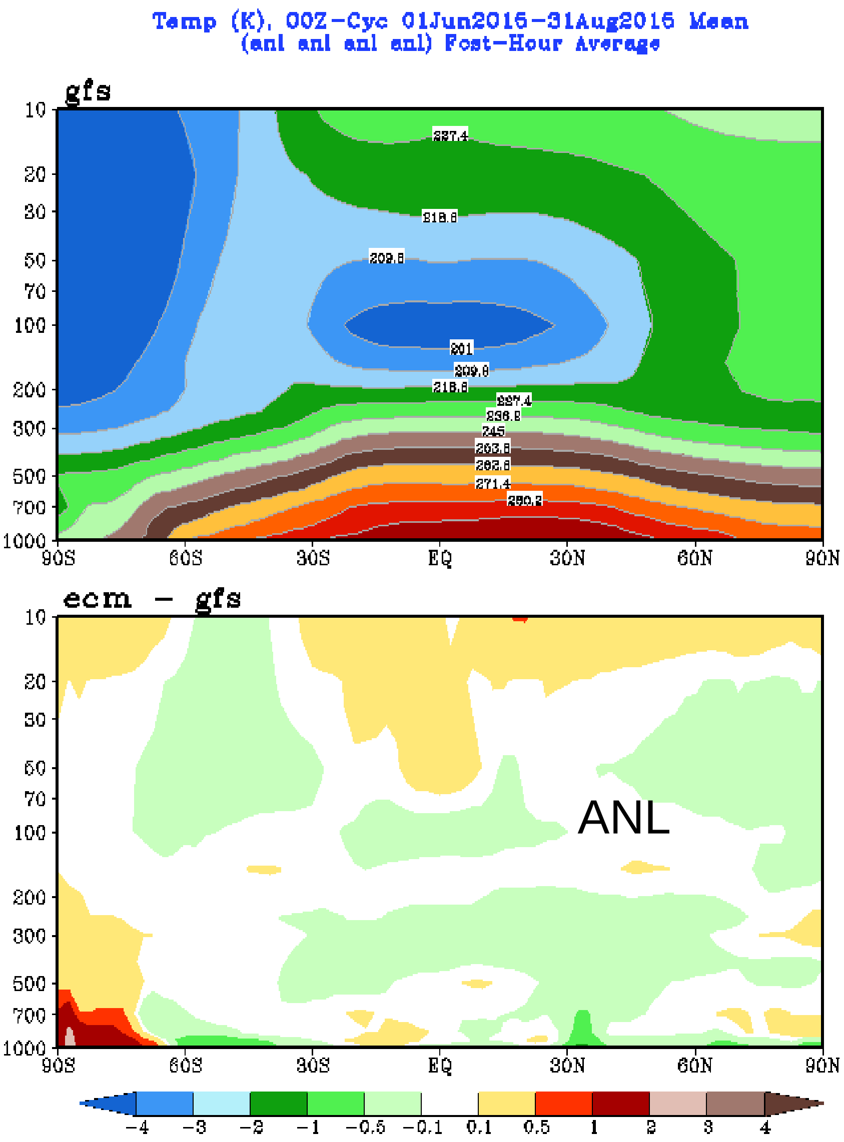


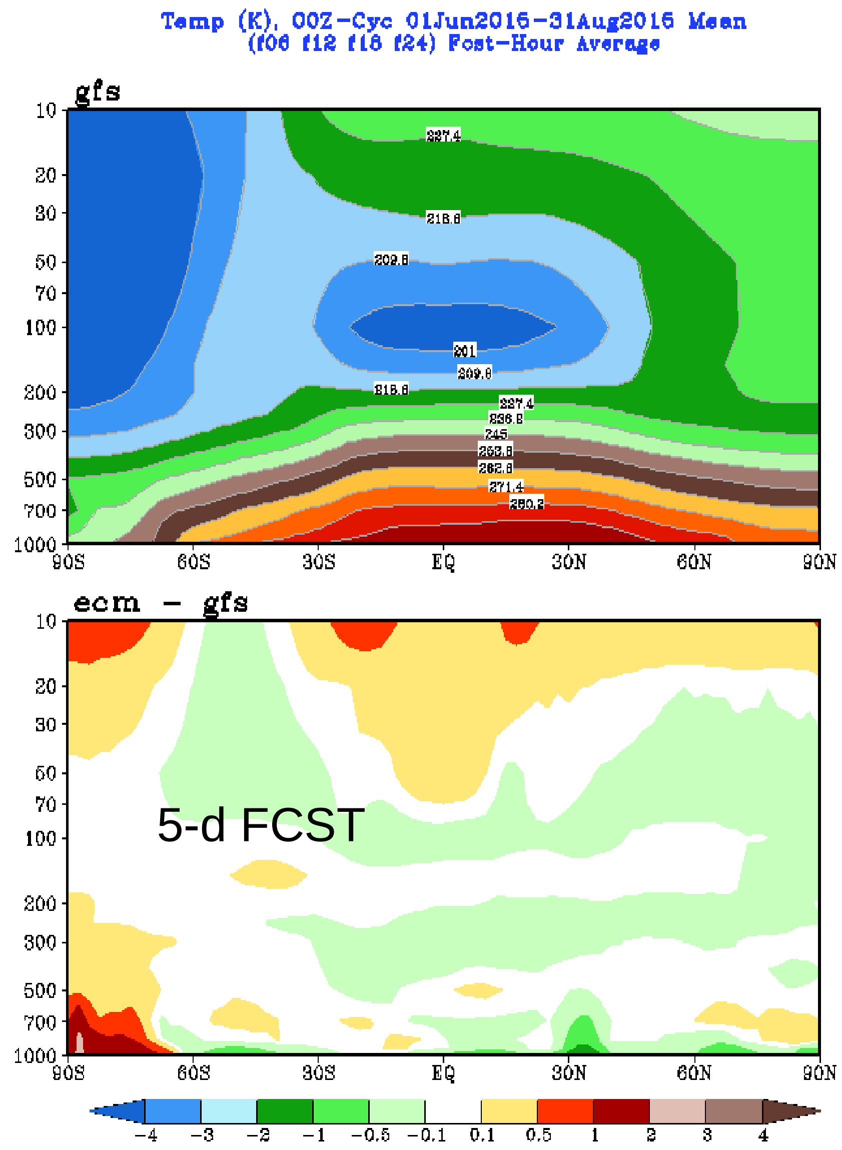
Tropics



http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/annual/2015/www/scorecard/mainindex.html
Scorecard

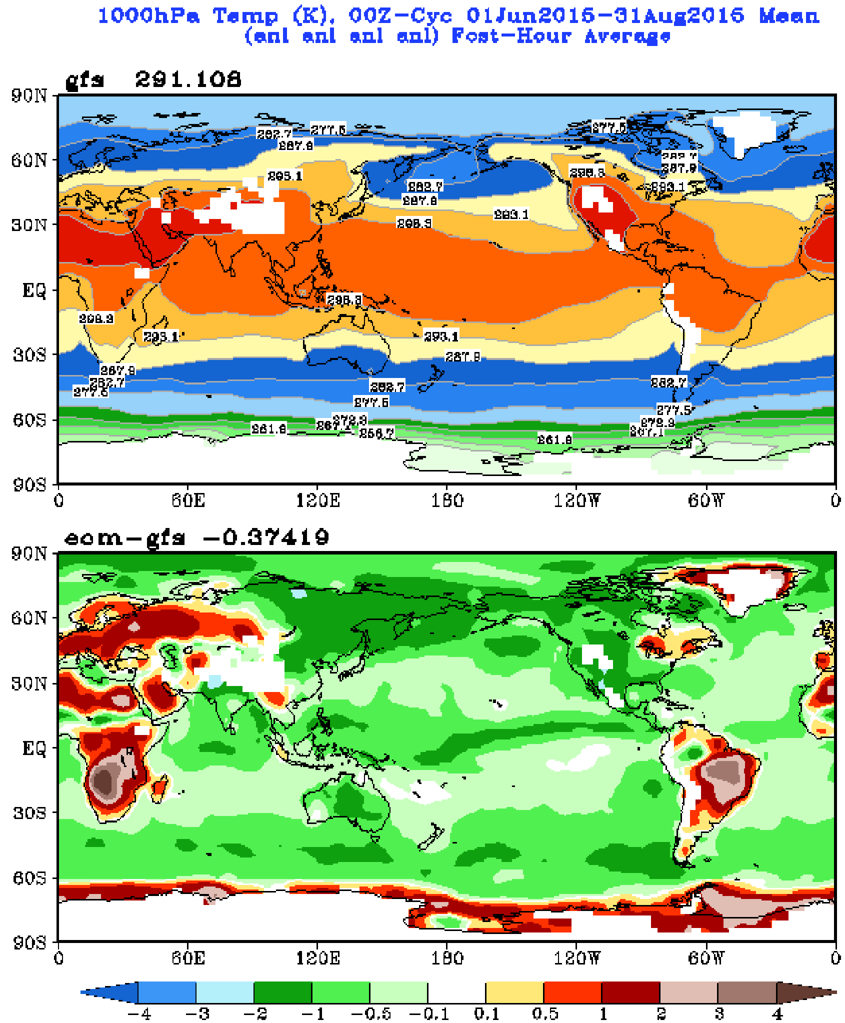
Zonal-Mean Temperature Analysis and Forecast Differences Between GFS and ECMWF (JJA 2015)



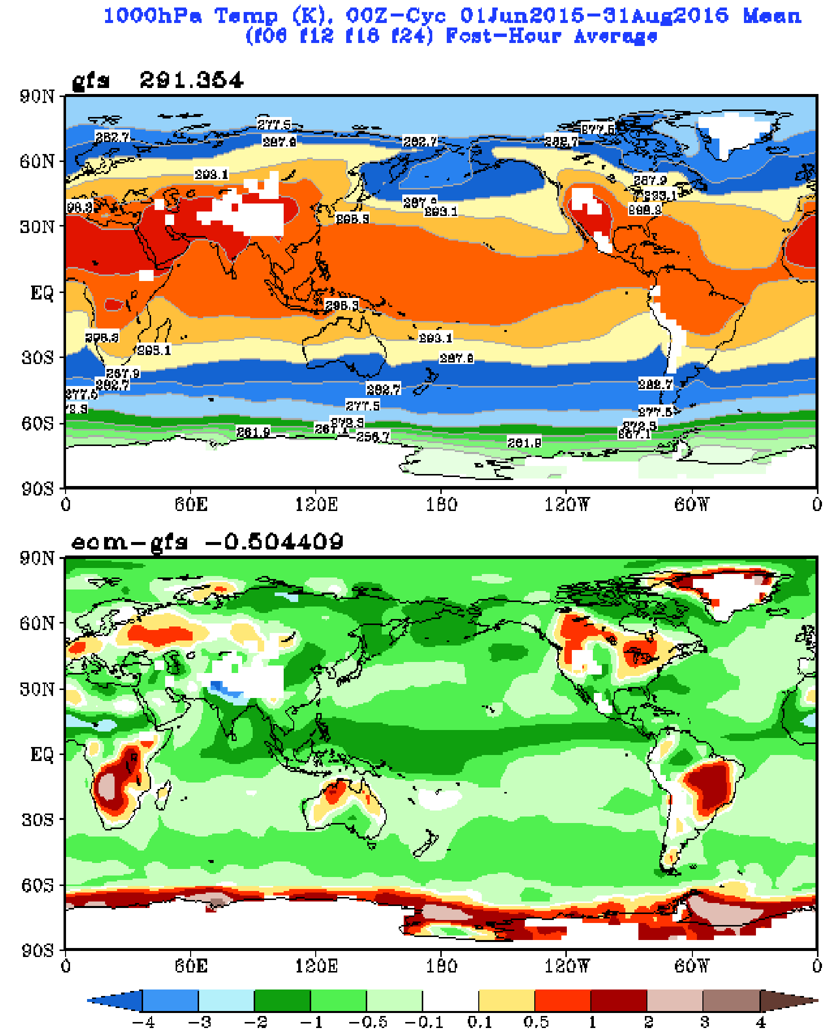


1000-hPa Temperature Analysis and Forecast Differences Between GFS and ECMWF (JJA 2015)

ANL

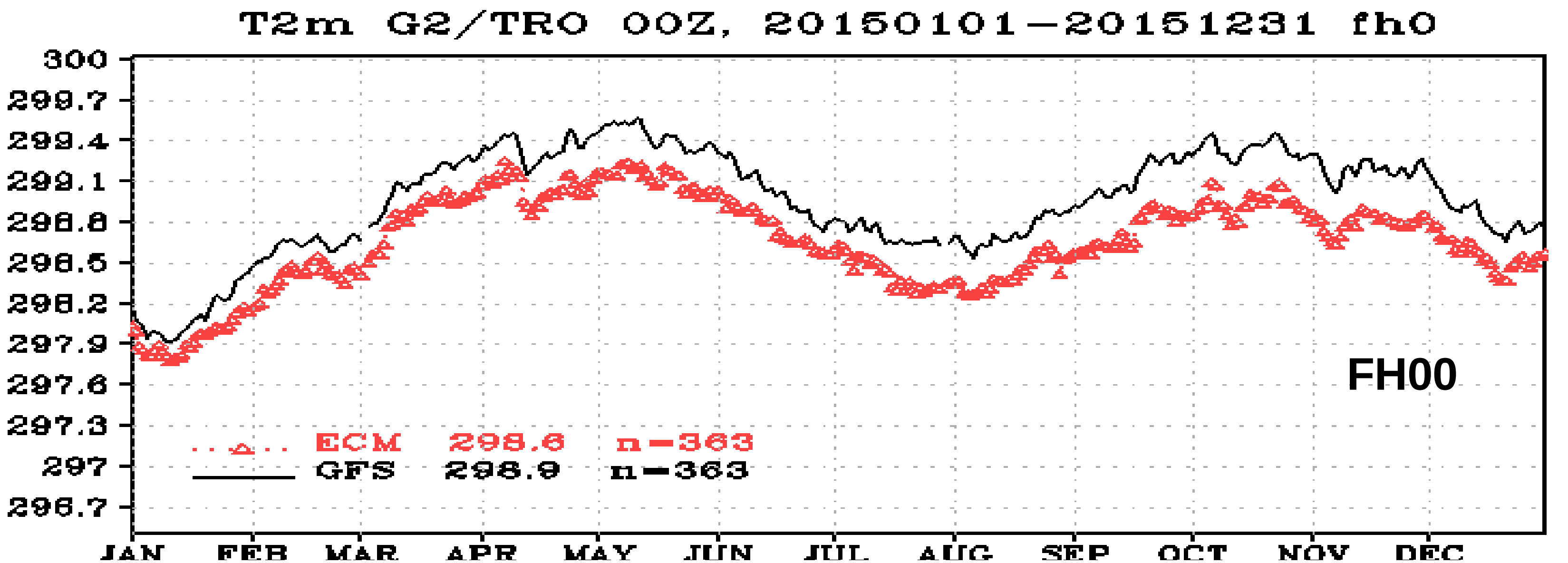


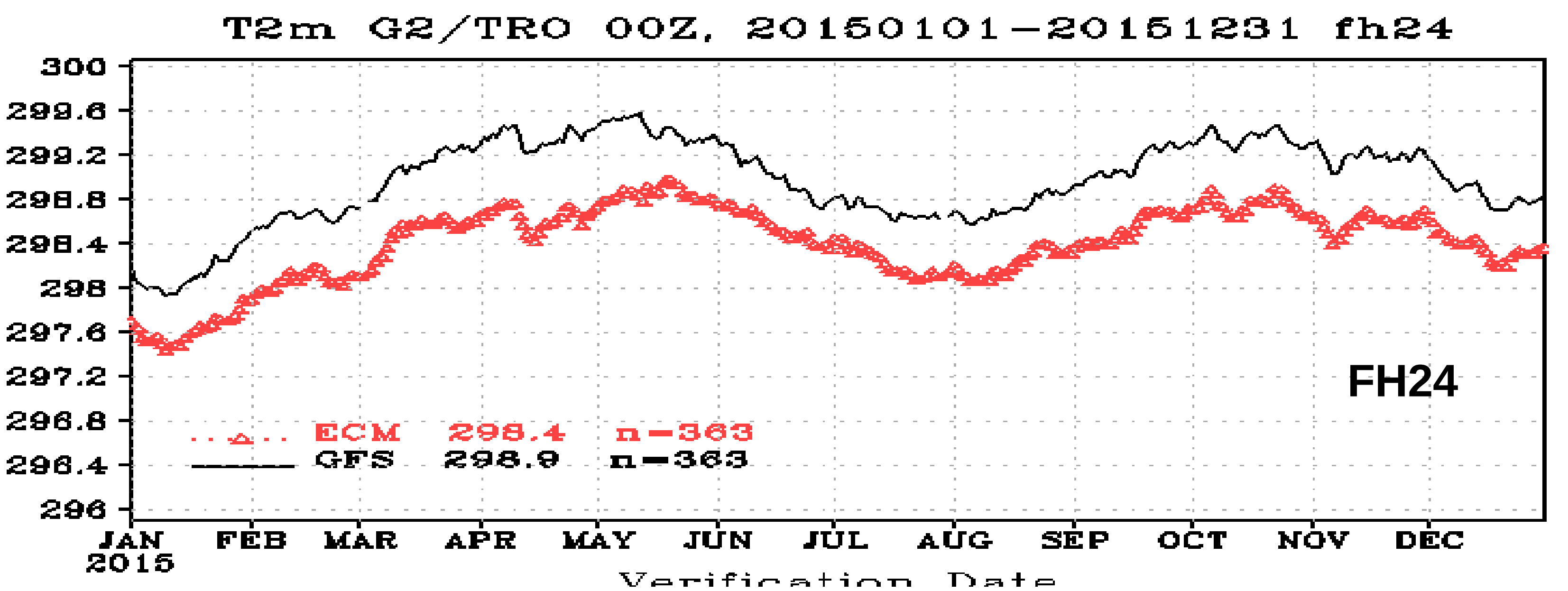
5-d FCST



Is GFS SST much warmer than ECMWF SST?

Tropical (20S-20N) Mean T2m

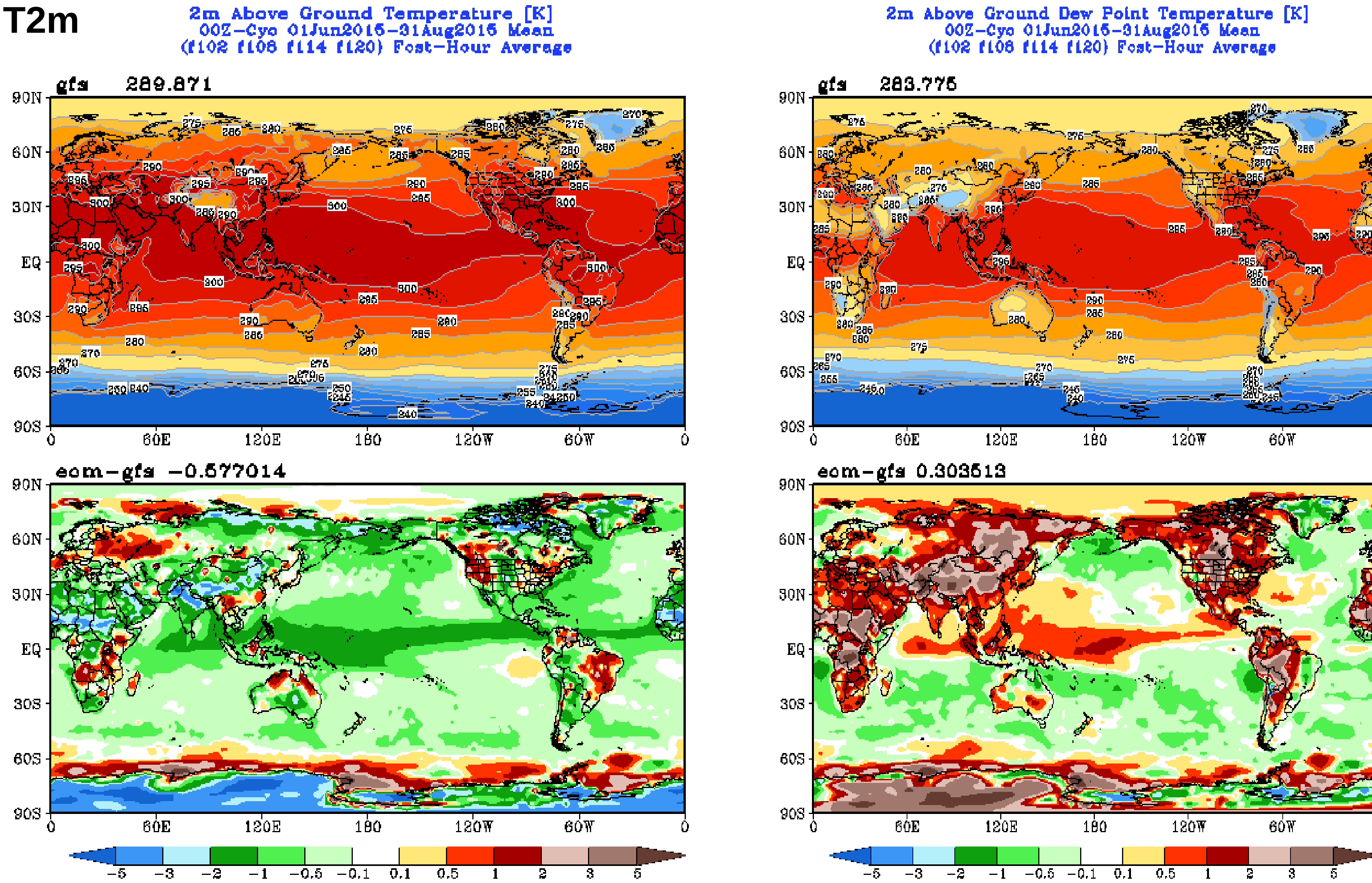




T2m and Td 5-day Forecast Differences Between GFS and ECMWF (JJA 2015)

T2m

Td



GFS Temperature Analysis Increment (June Mean)

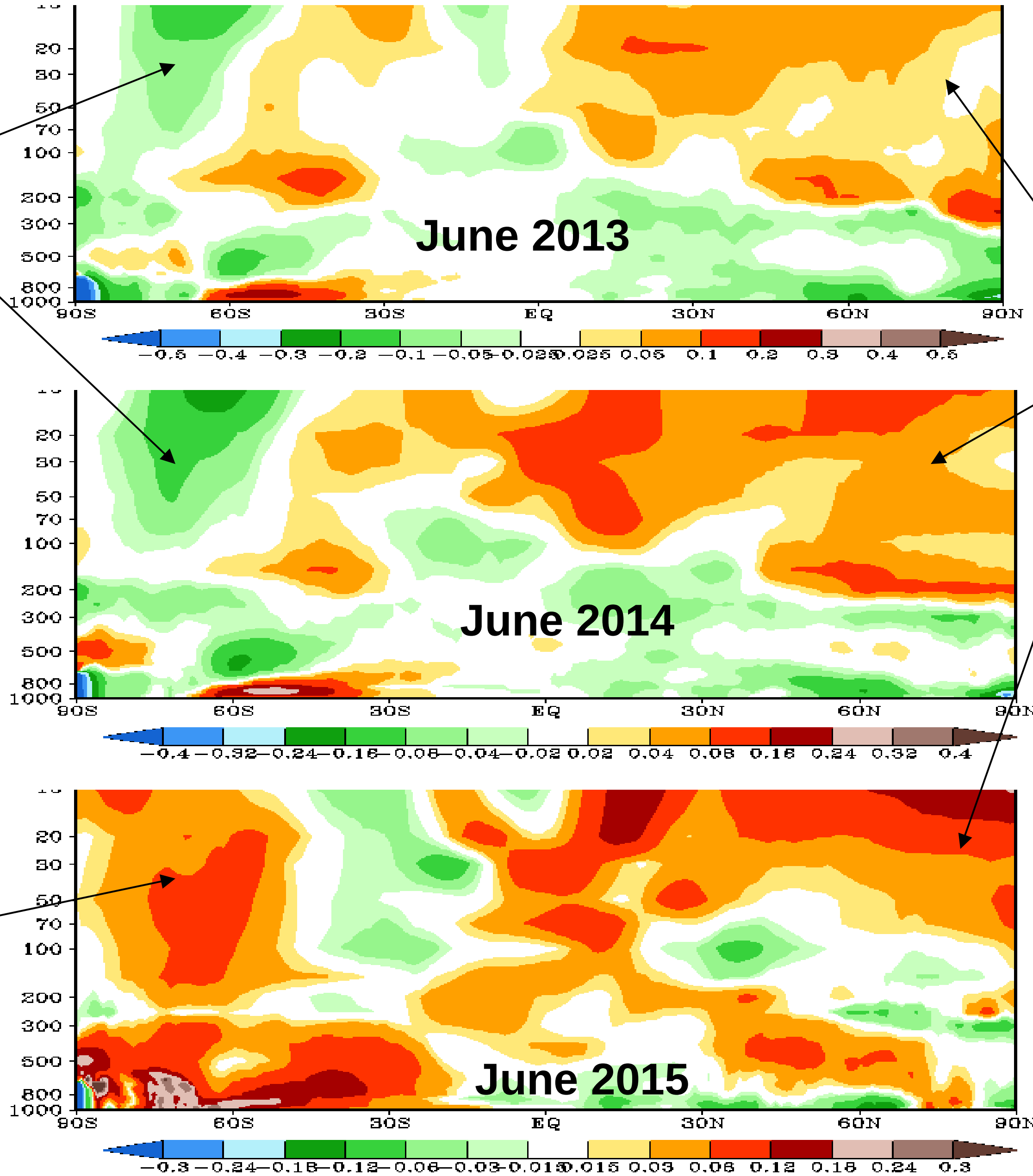
Model too warm

T574 Eulerian GFS

T1534 SLG GFS

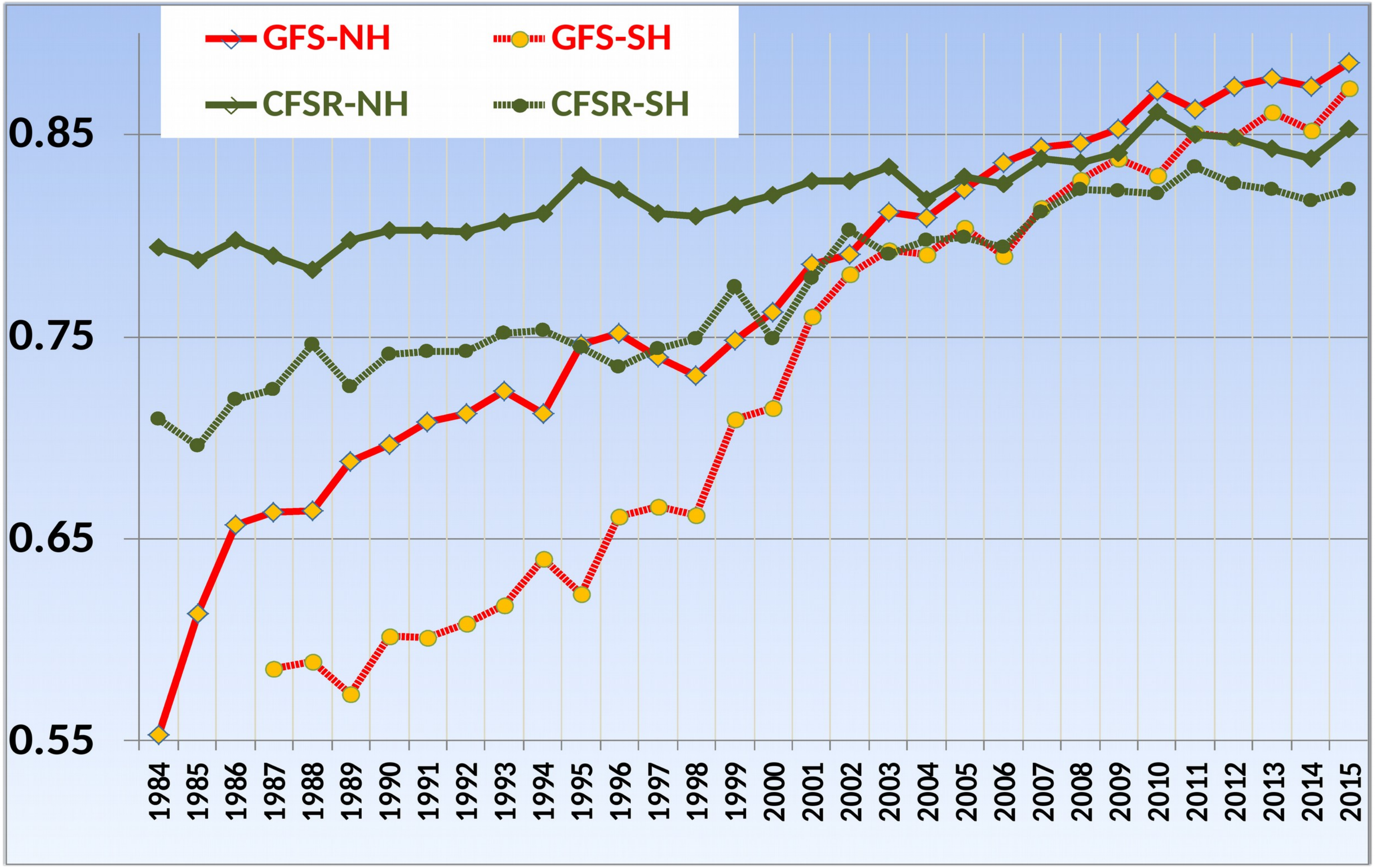
Model too cold

Model too cold



Historical Score

Annual Mean 500-hPa HGT Day-5 Anomaly Correlation

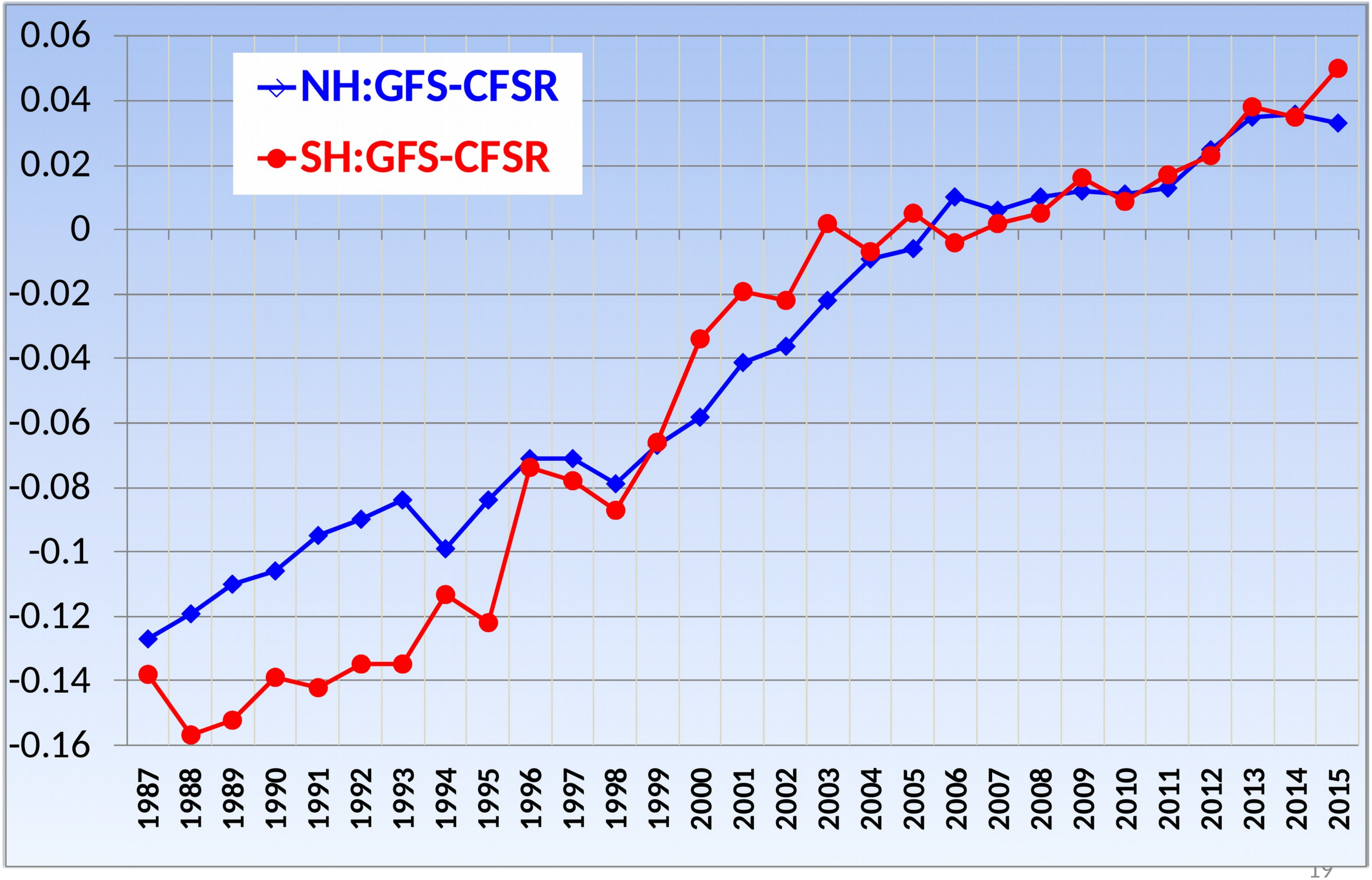


Increase is about 0.1 per decade

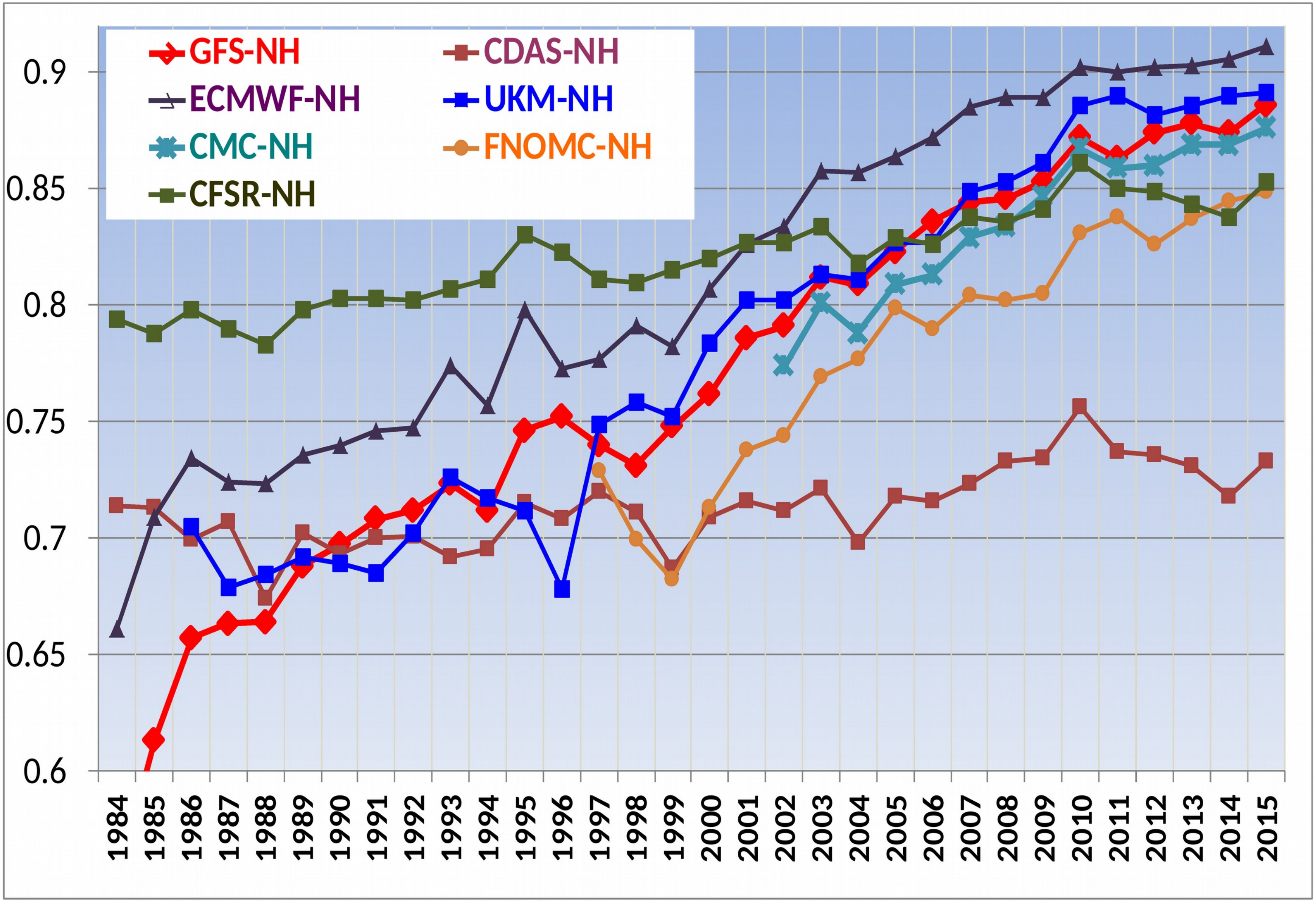
CDAS is a legacy GFS (T64) used for NCEP/NCAR Reanalysis circa 1995.

CFSR is the coupled GFS (T126) used for reanalysis circa 2006.

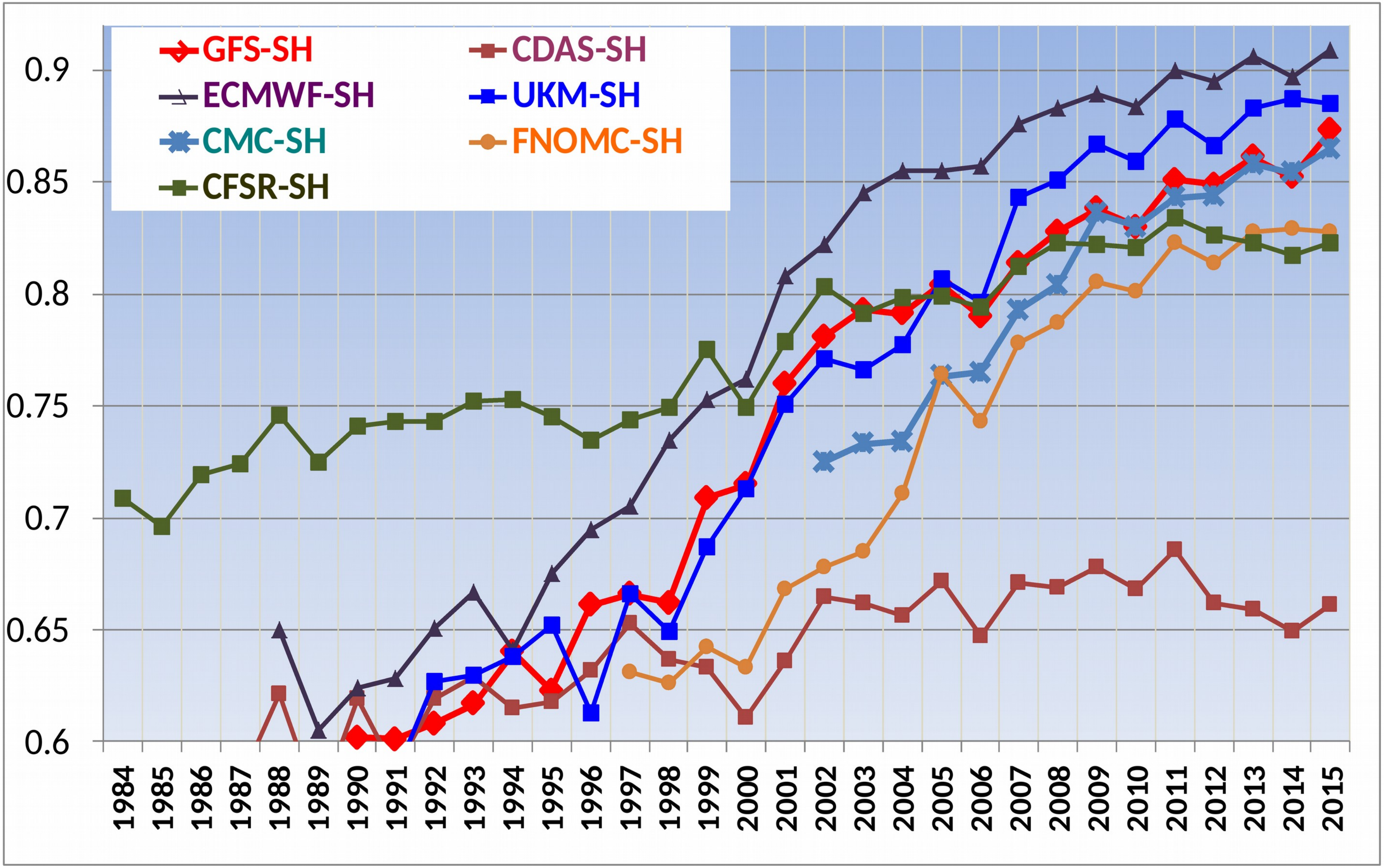
Annual Mean 500-hPa HGT Day-5 Anomaly Correlation
GFS minus CFSR



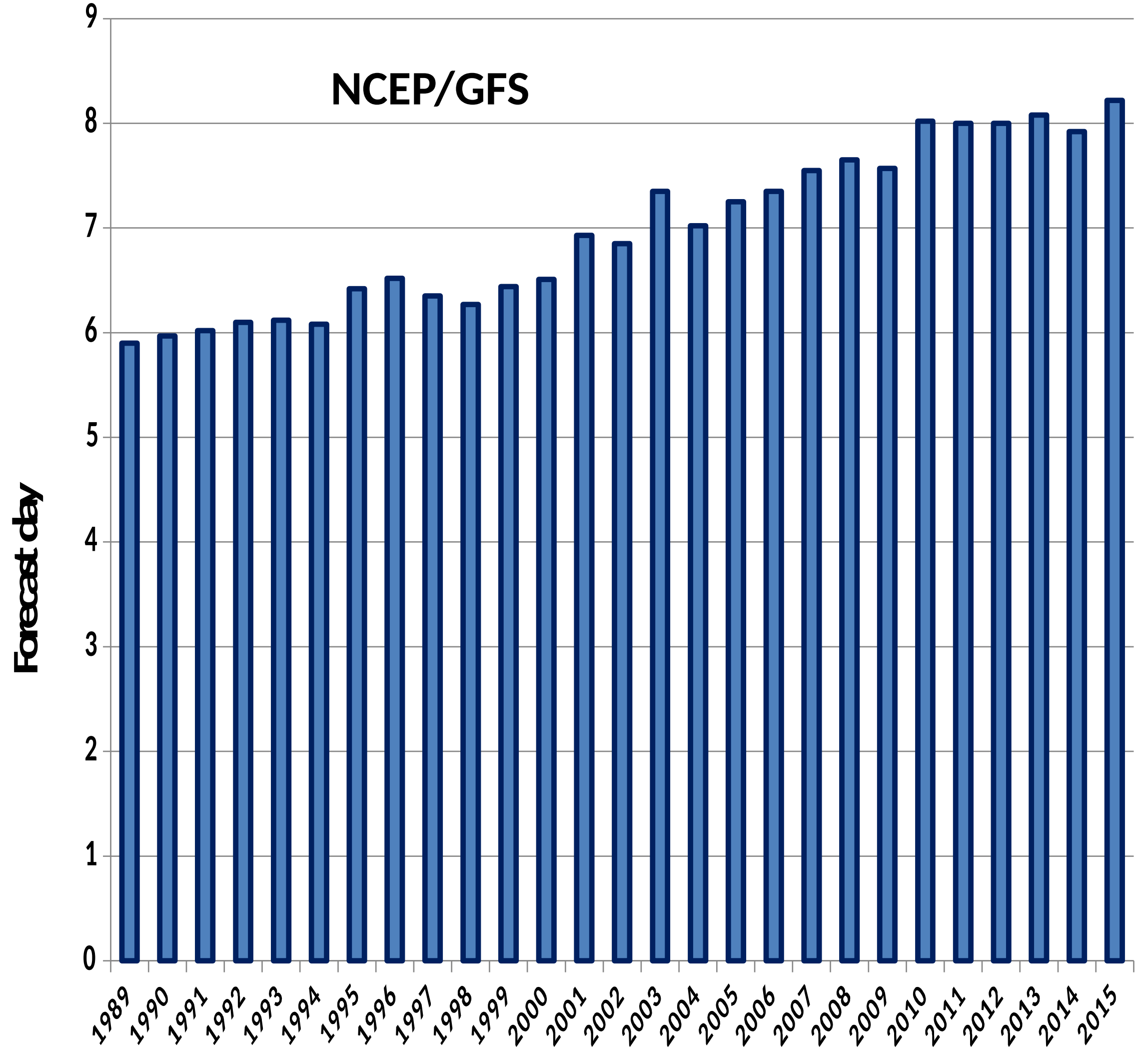
Annual Mean NH 500hPa HGT Day-5 AC



Annual Mean SH 500hPa HGT Day-5 AC



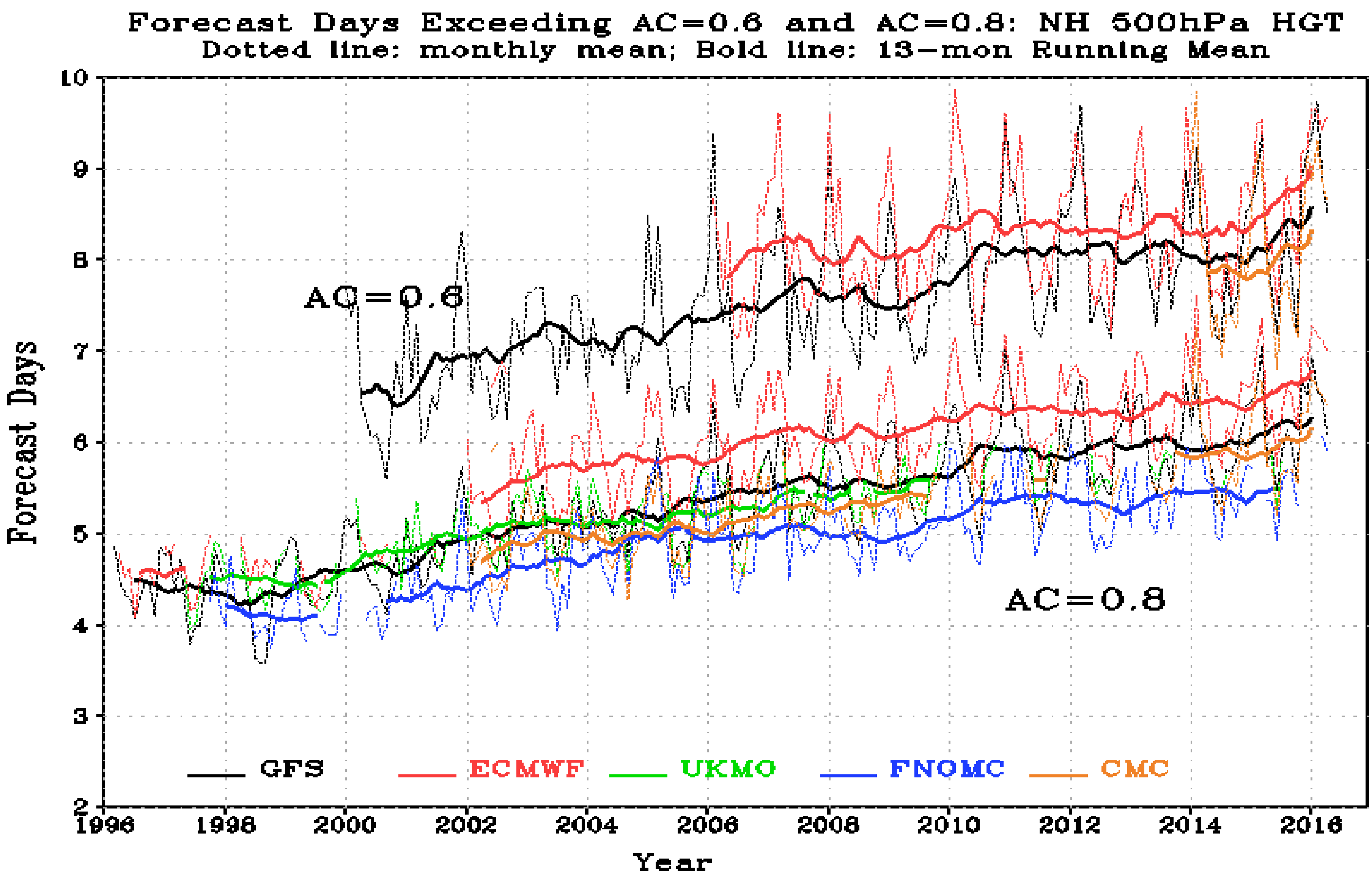
Day at which forecast loses useful skill (AC=0.6) N. Hemisphere 500hPa height calendar year means



8.22d

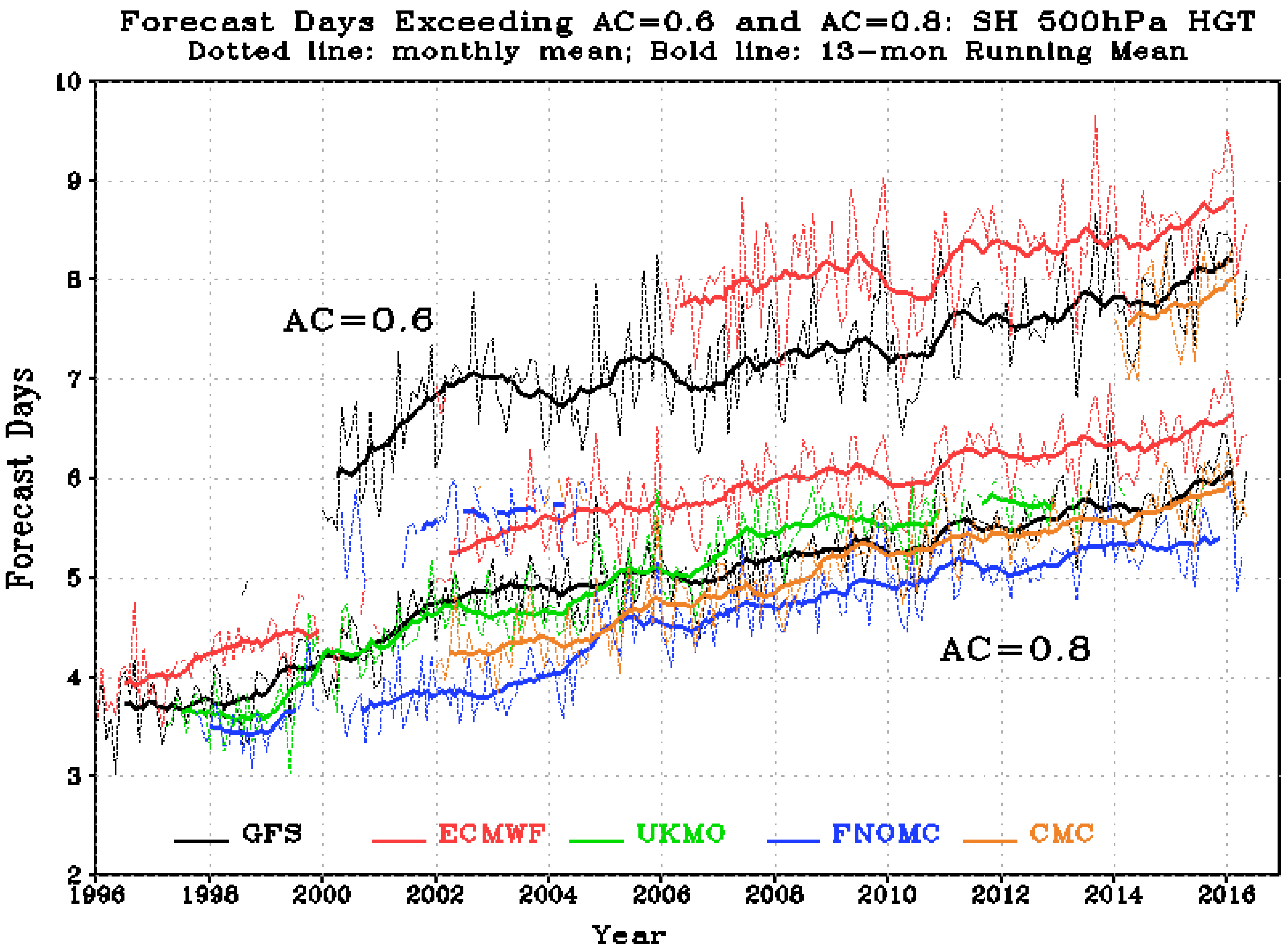
7.92d

Useful Forecast Days for Major NWP Models, NH



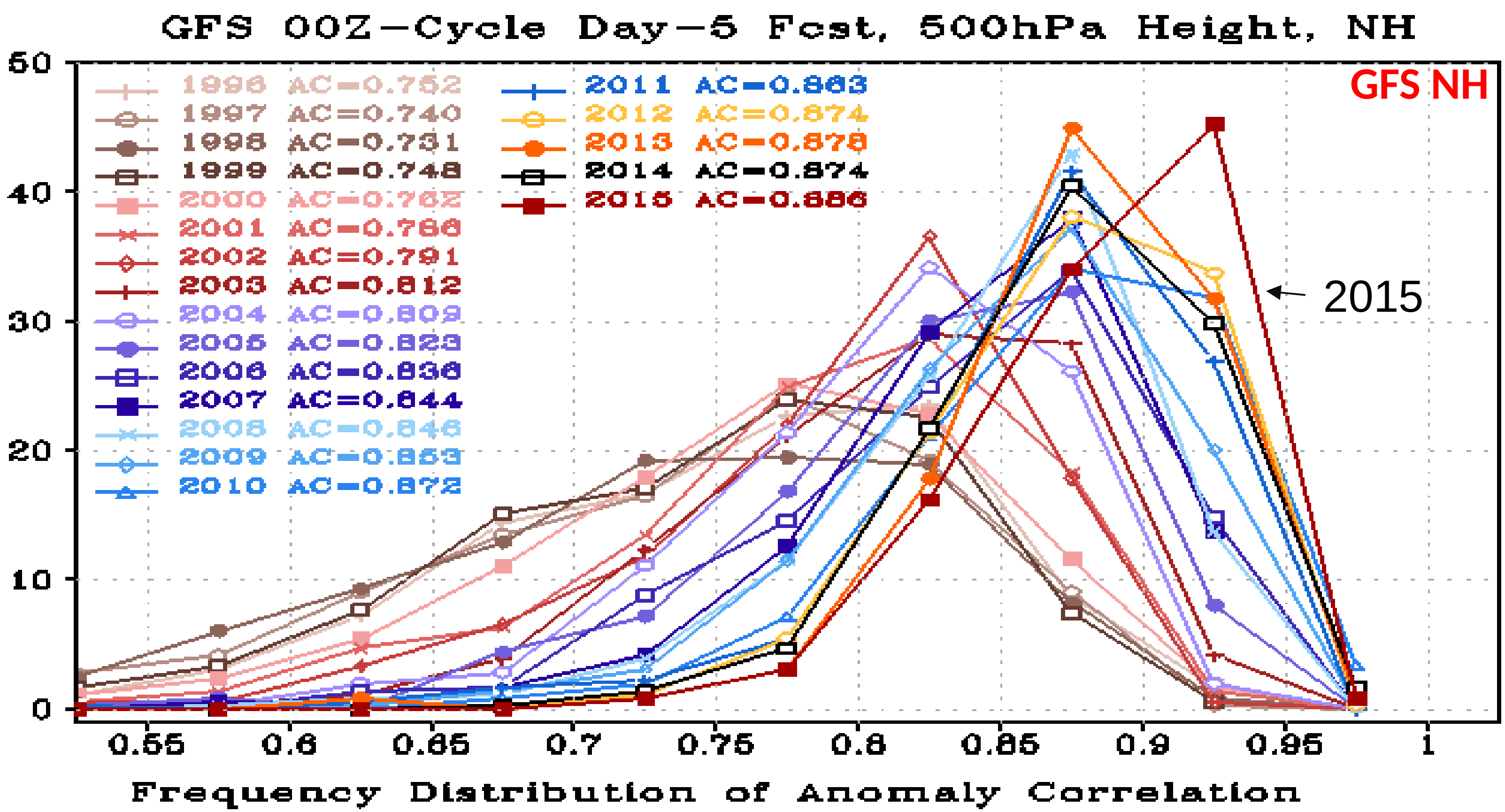
http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/longterm/

Useful Forecast Days for Major NWP Models, SH



AC Frequency Distribution

Twenty bins were used to count for the frequency distribution, with the 1st bin centered at 0.025 and the last been centered at 0.975. The width of each bin is 0.05.



- Jan 2000: T126L28 T170L42
- May 2001: prognostic cloud
- Oct 2002: T170L42 T254L64
- May 2005: T254L64 T382L64;
  2-L OSU LSM 4-L NOHA LSM

- May 2007: SSI GSI Analysis;
  Sigma sigma-p hybrid coordinate
- July 2010: T382L64 T574L64; Major Physics Upgrade
- May 2012: Hybrid-Ensemble 3D-VAR Data Assimilation
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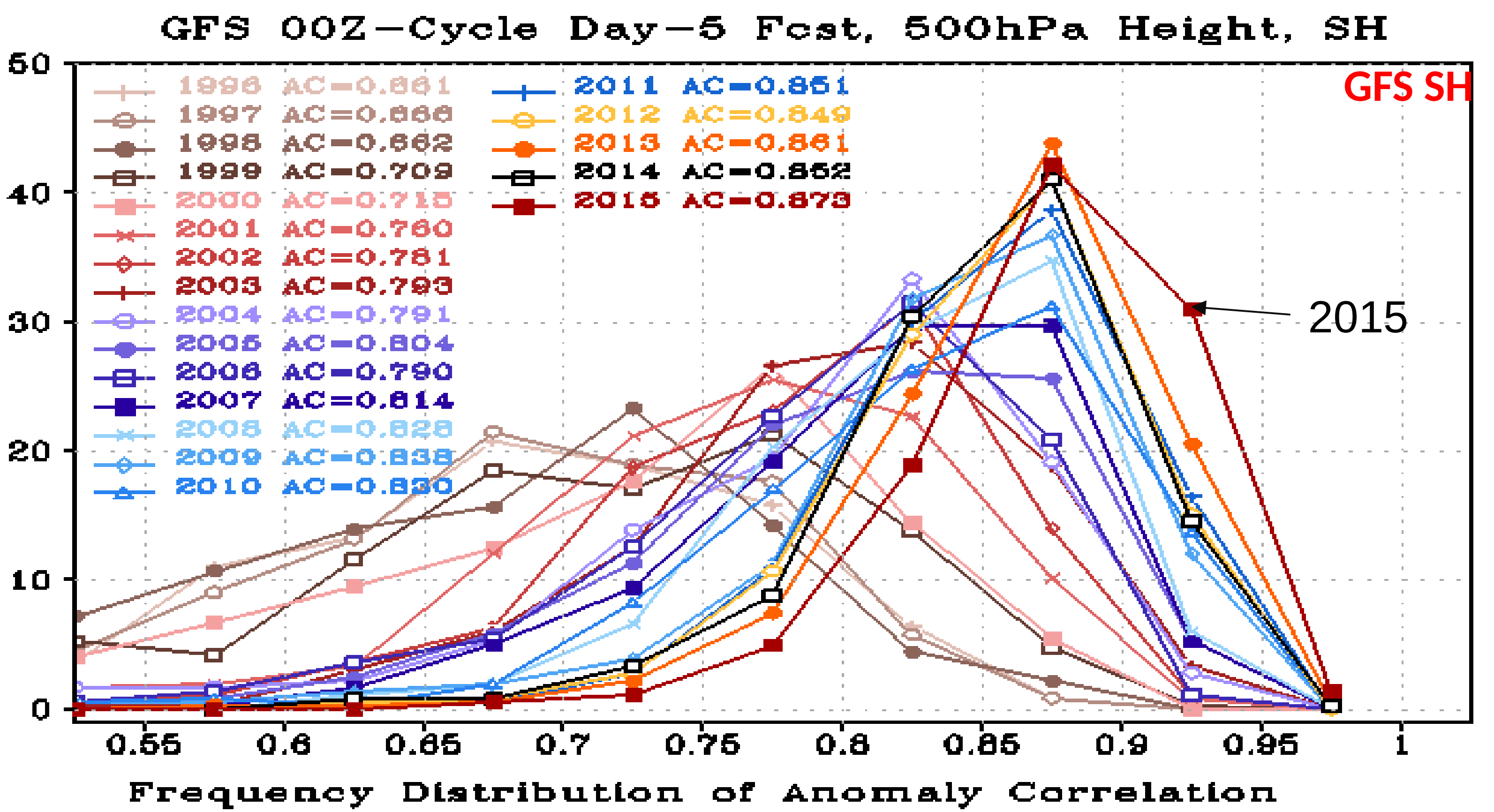
- Jan 2015: T1534 SL-GFS

AC Frequency Distribution



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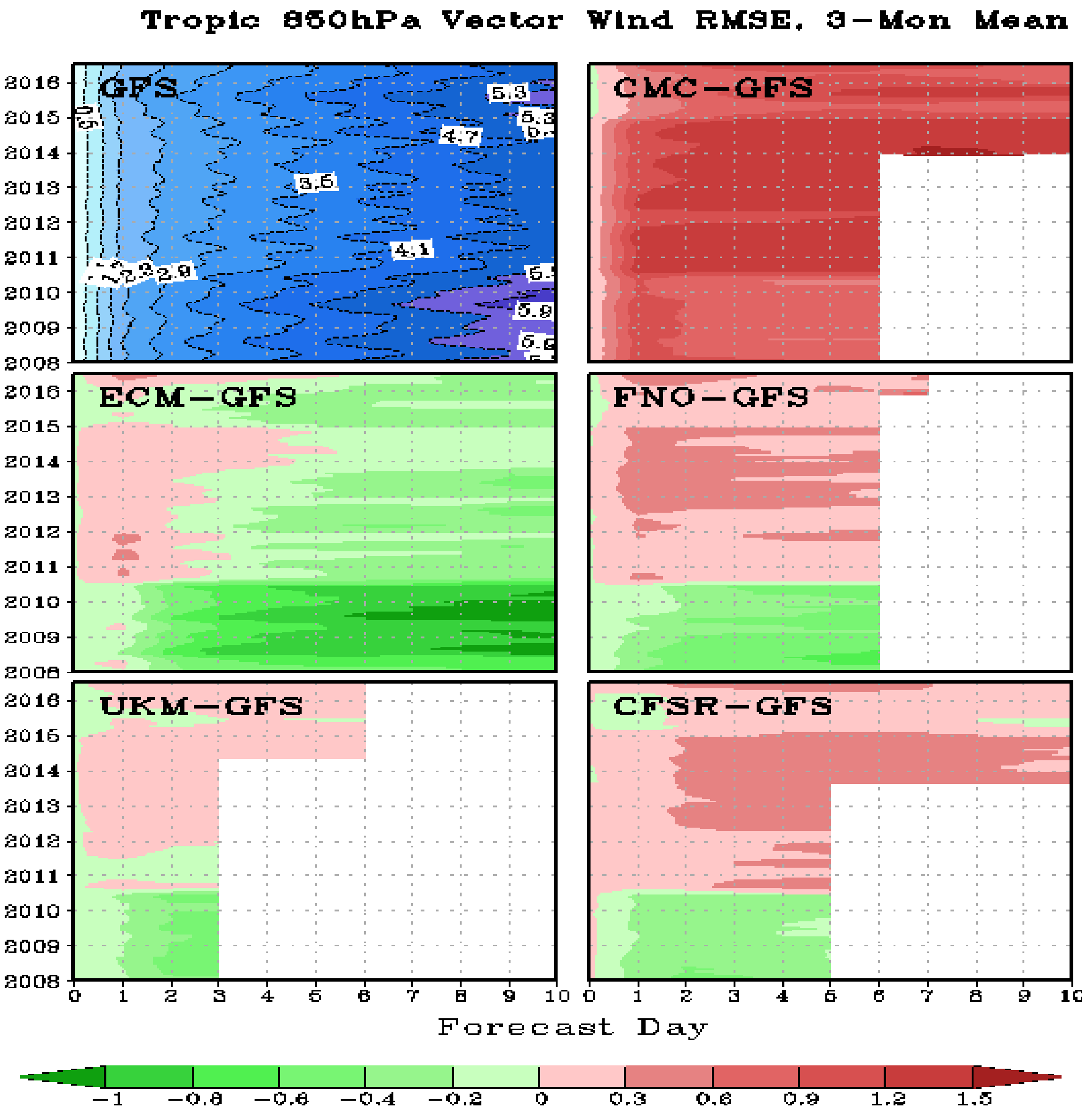
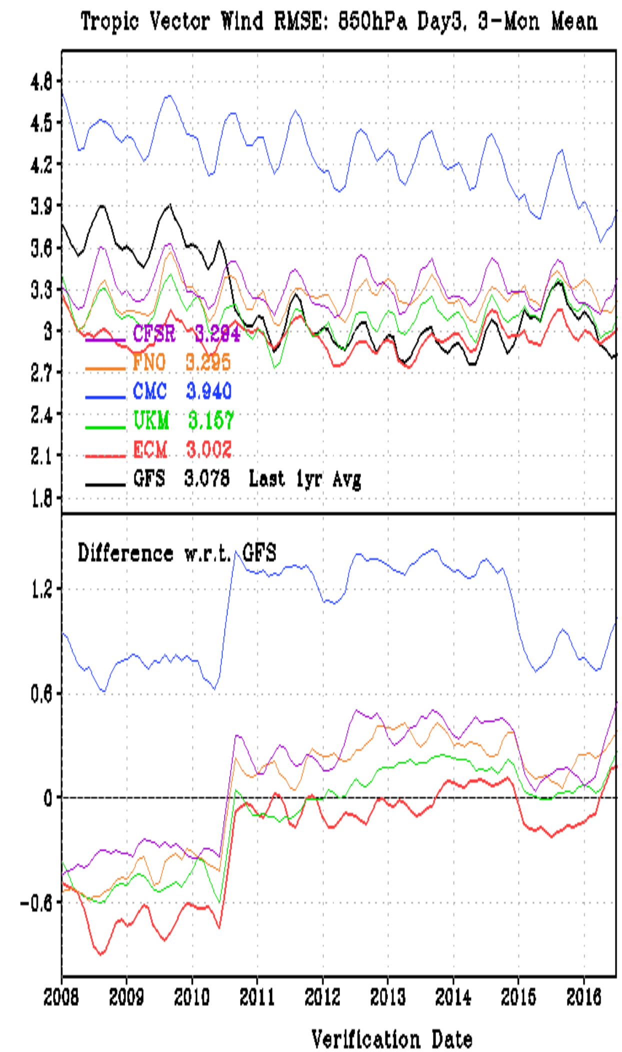
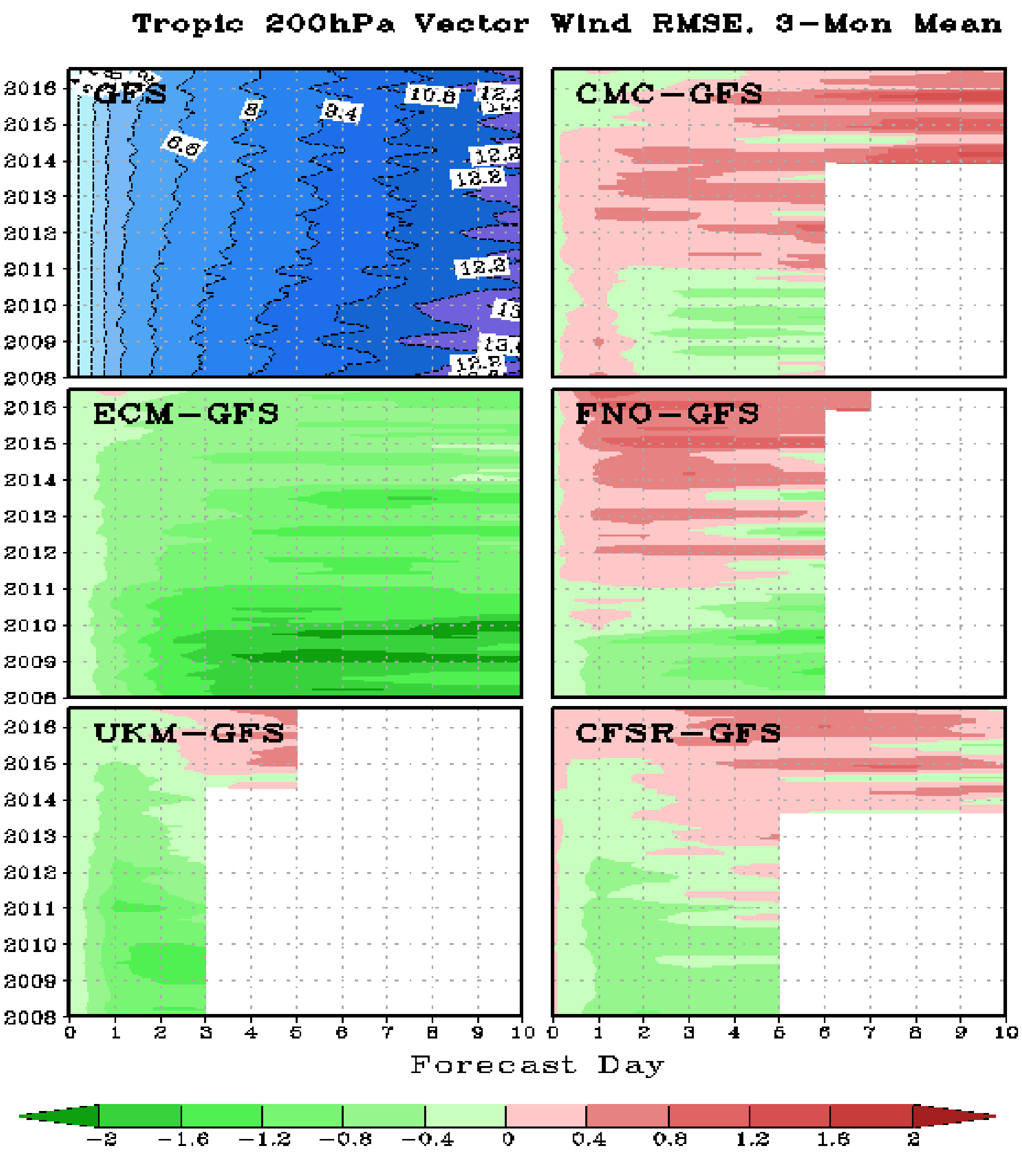
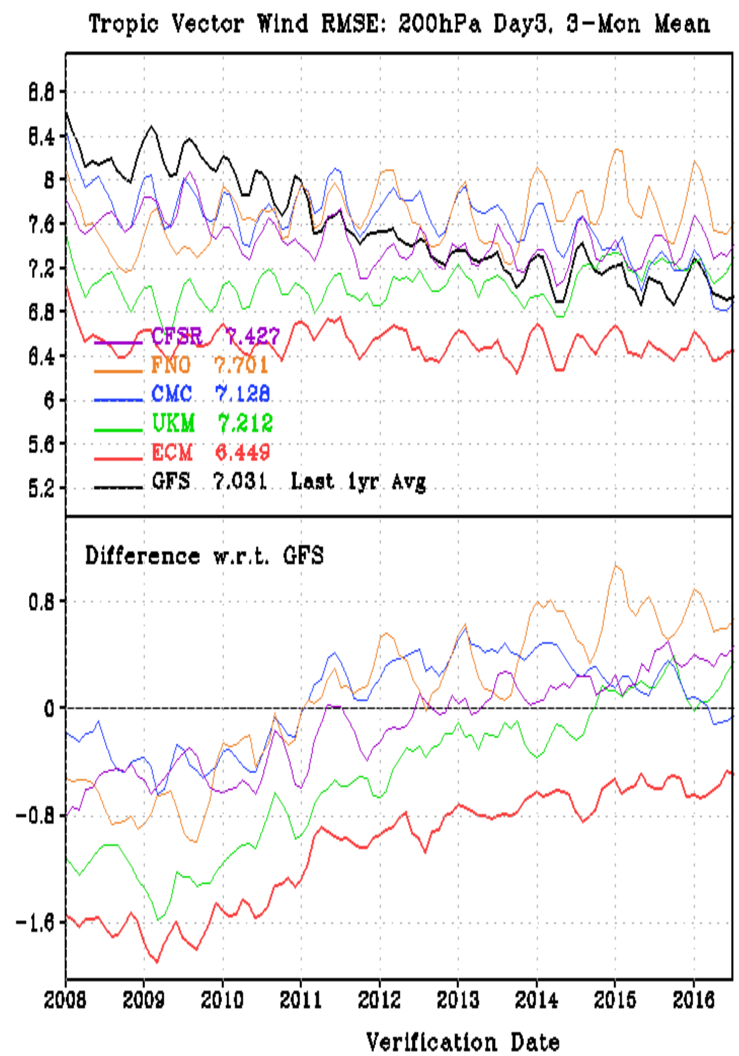
Tropical Wind RMSE (850 hPa, Jan2008-Jun2016)





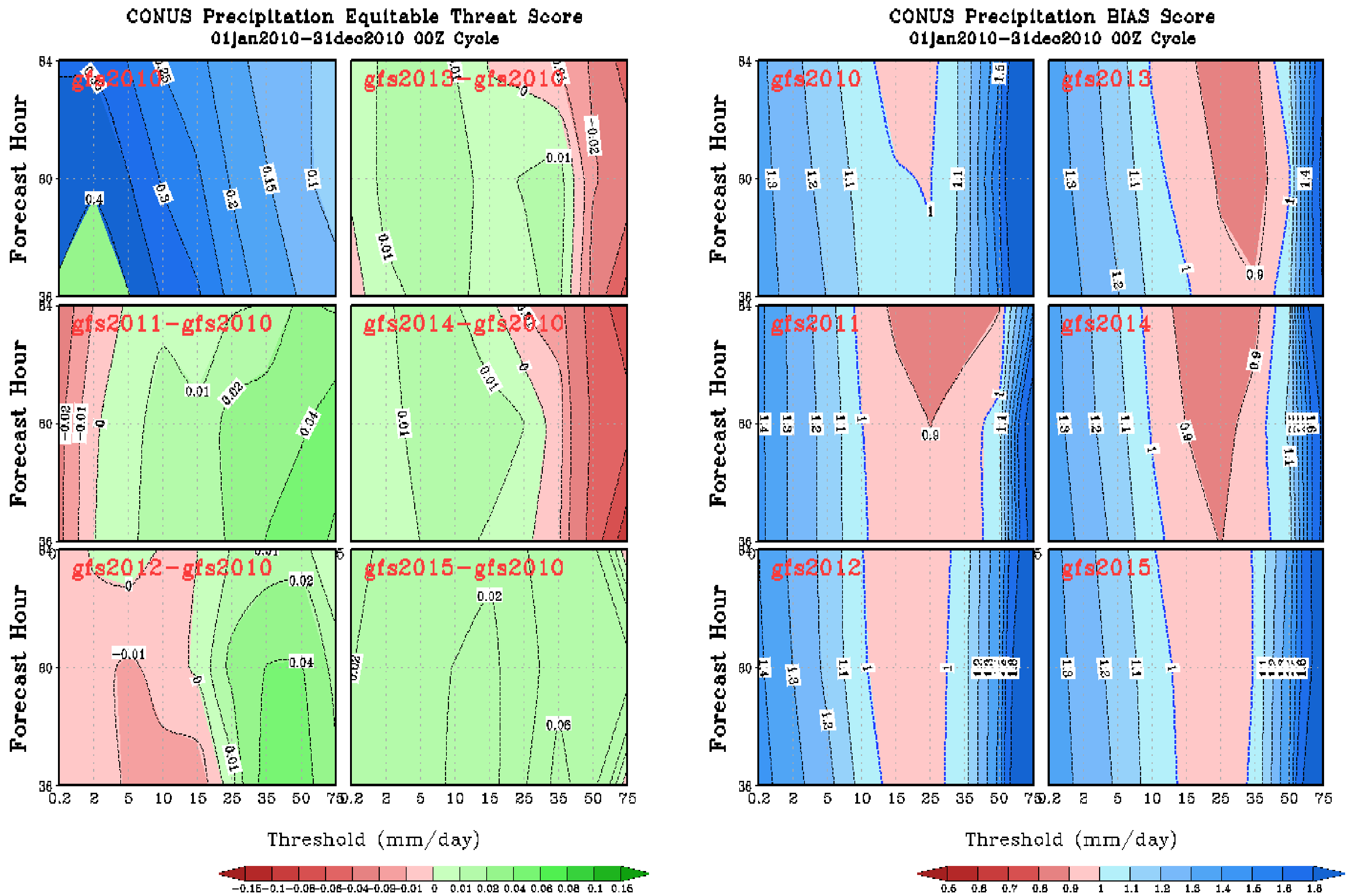
Tropical Wind RMSE (200 hPa, Jan2008-Jun2016)



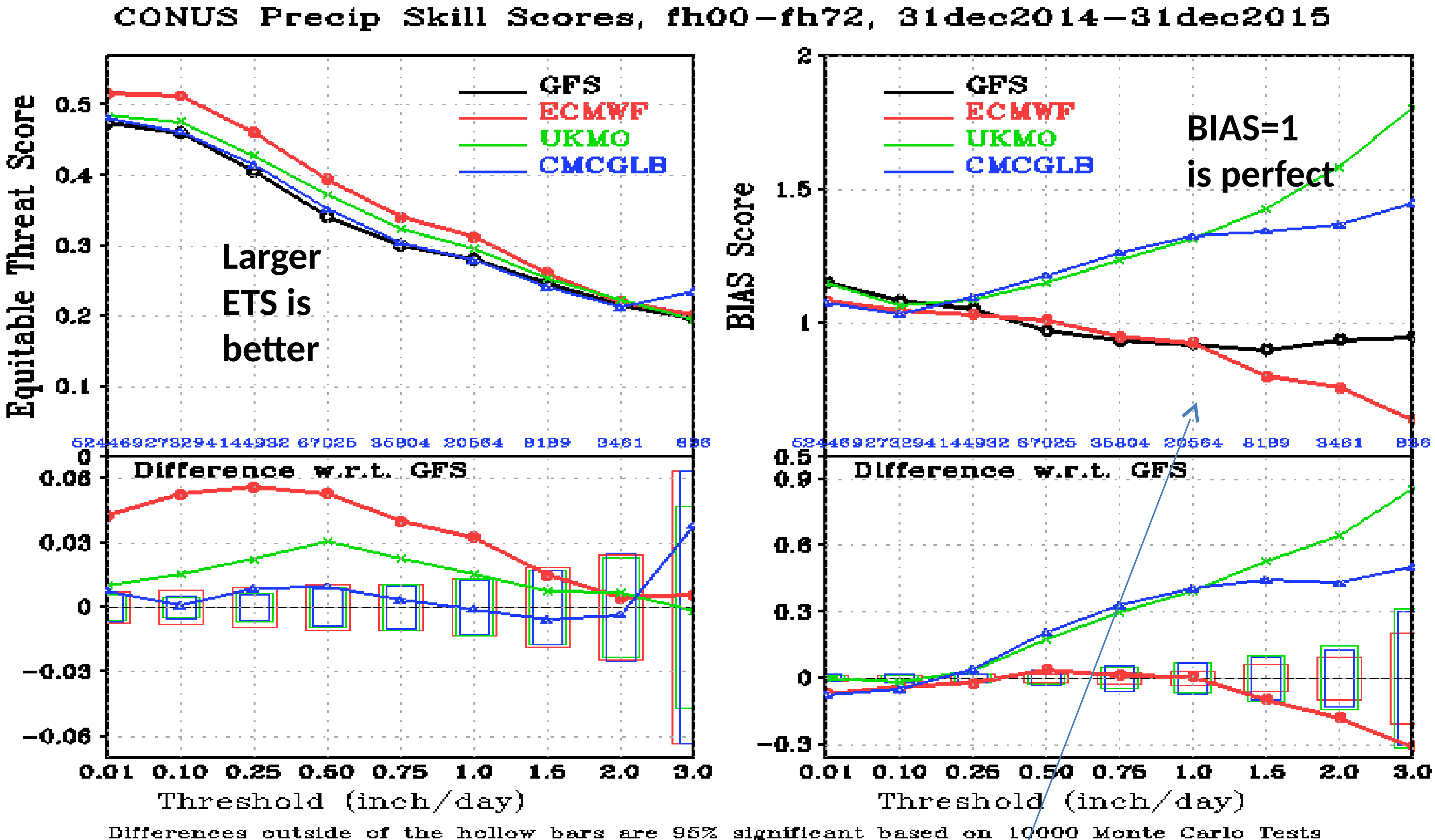


Precipitation

GFS Annual Precip ETS and BIAS Scores over CONUS

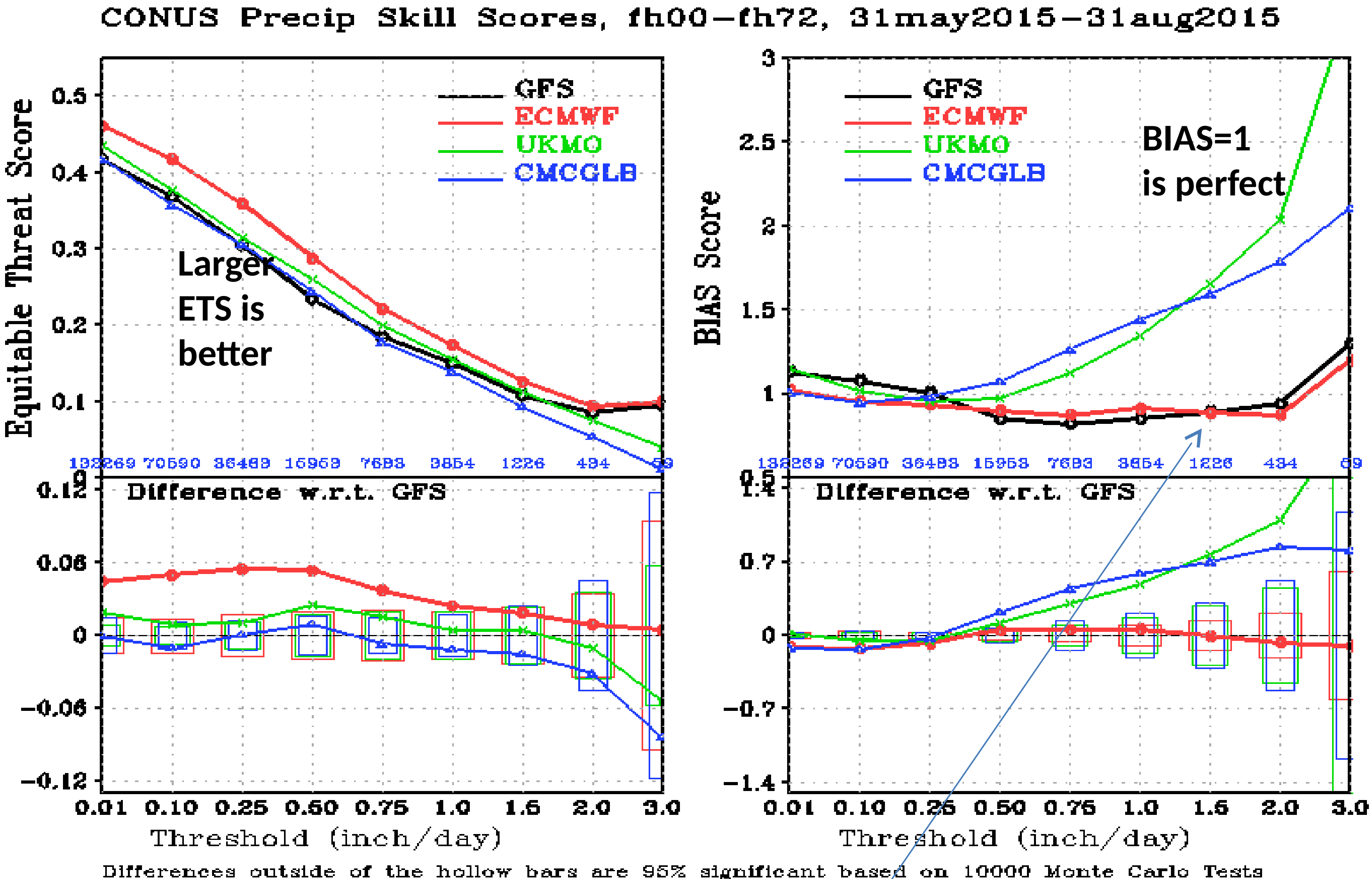


2015 Annual Mean CONUS Precipitation Skill Scores, 00-72 hour Fcst



- **ECMWF has the best ETS score.**
- **Both GFS and ECMWF underestimated moderate and heavy rainfall events. UKM and CMC had large wet biases.**

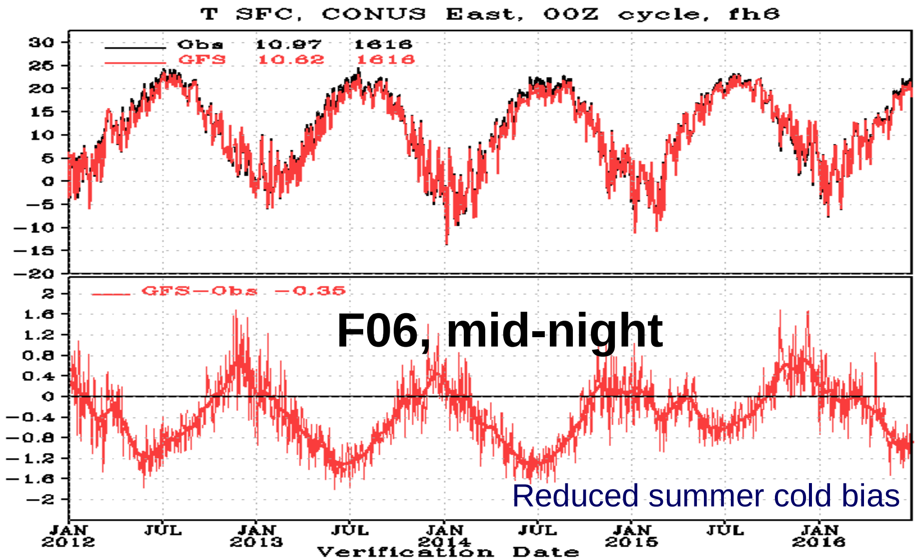
2015 JJA CONUS Precipitation Skill Scores, 00-72 hour Forecast

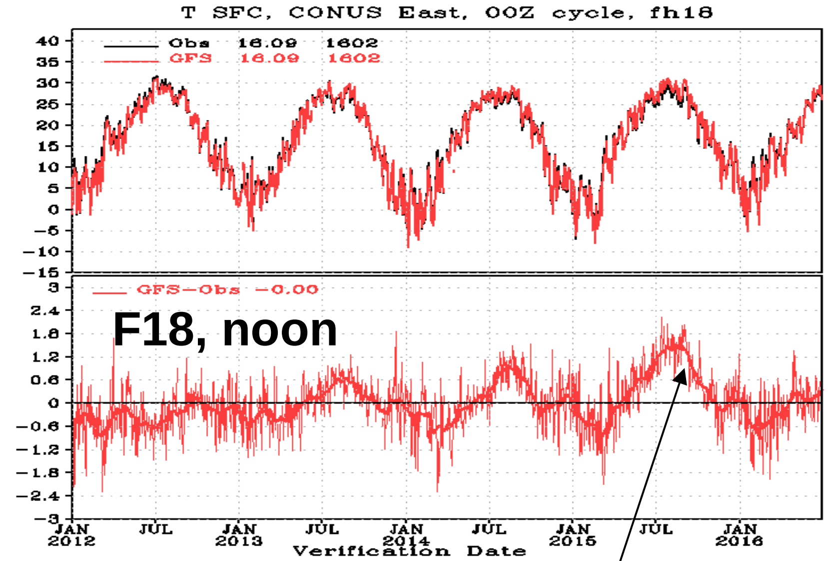


- **ECMWF had the best ETS score. GFS, UKM and CMC were close to each other.**
- **ECMWF underestimated heavy rainfall events. GFS was dry for moderate rainfall events..**

Verification against Surface and Rawinsonde Observations

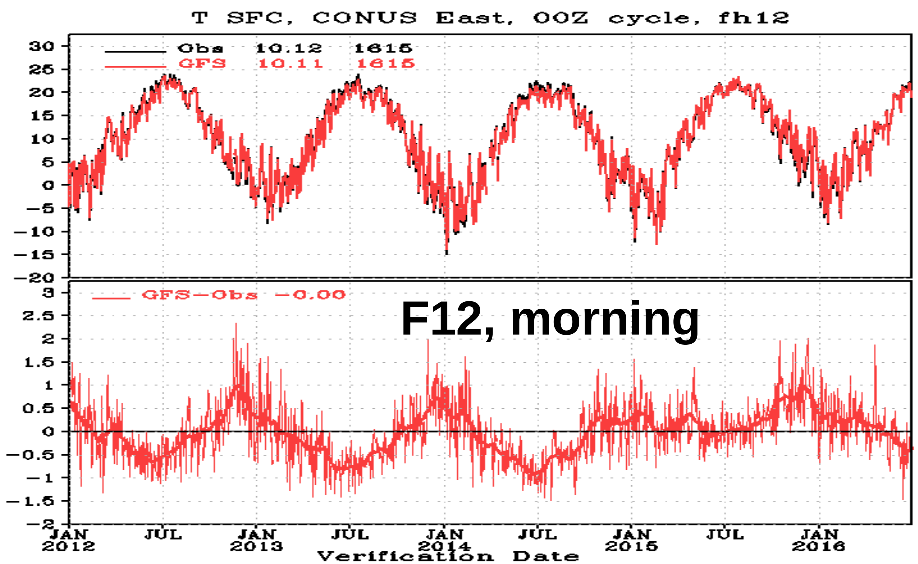
T2m over CONUS East, Jan2012 ~ Jun2016

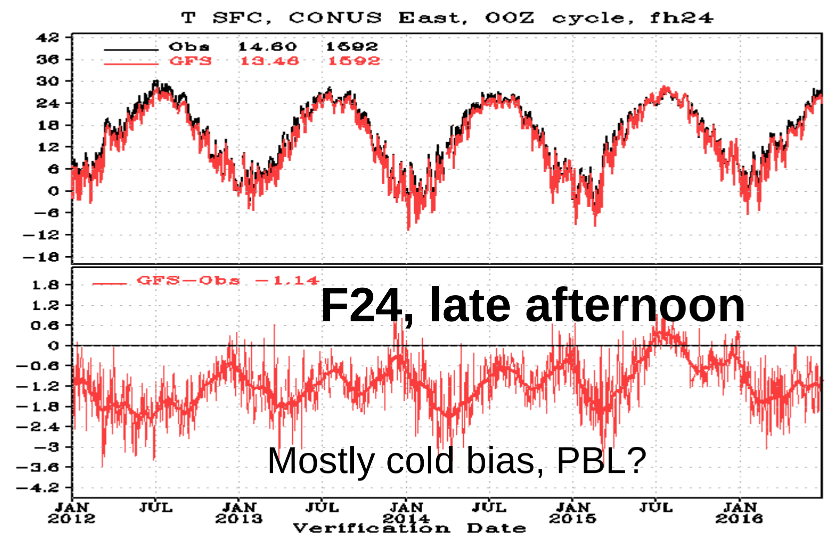




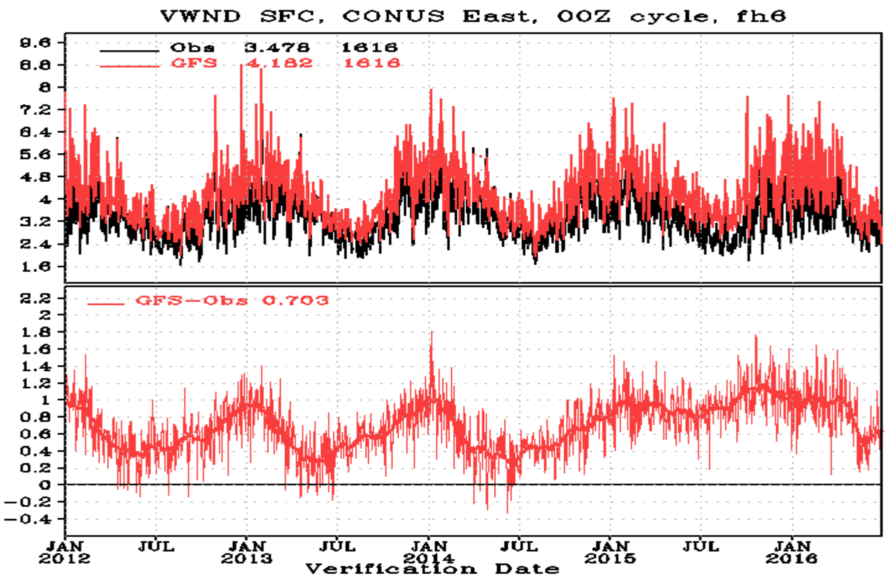
T574 Eulerian | *T1534 SLG*

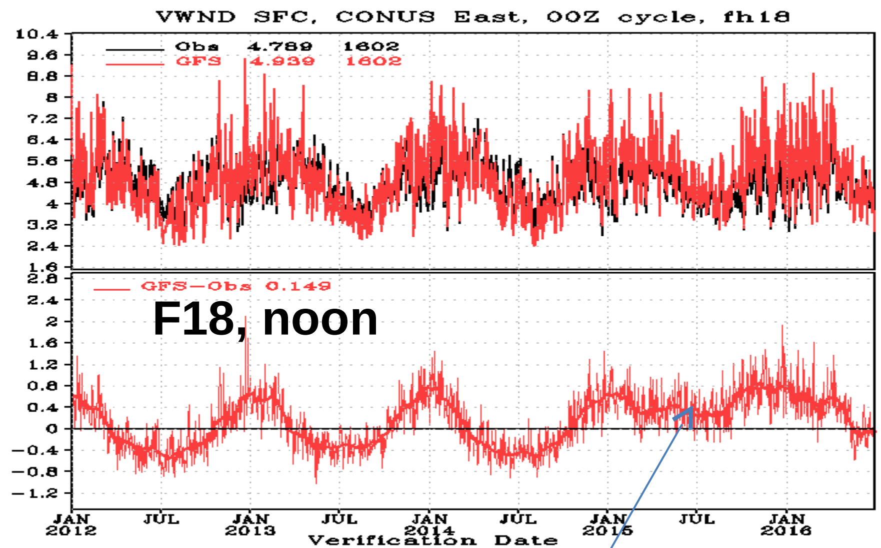
2015 summer warm bias





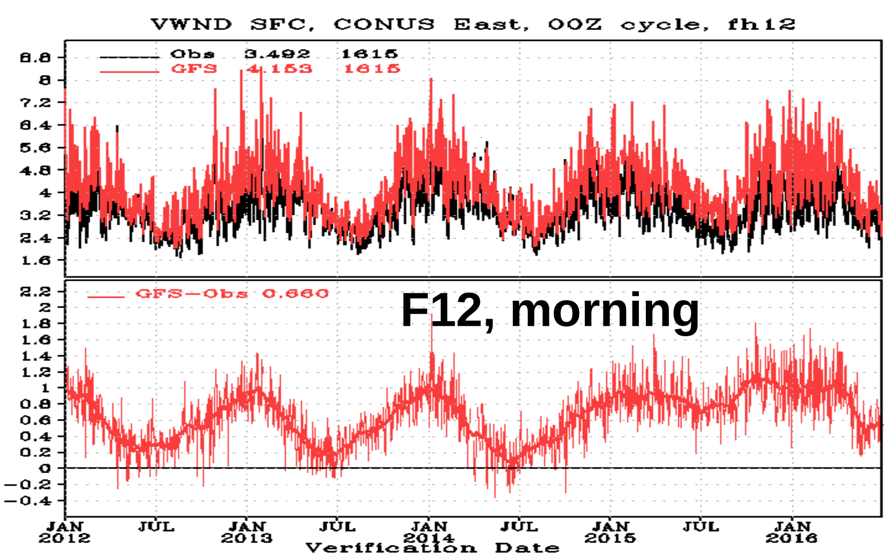
10-m Wnds over CONUS East, Jan2012 ~ Jun2016

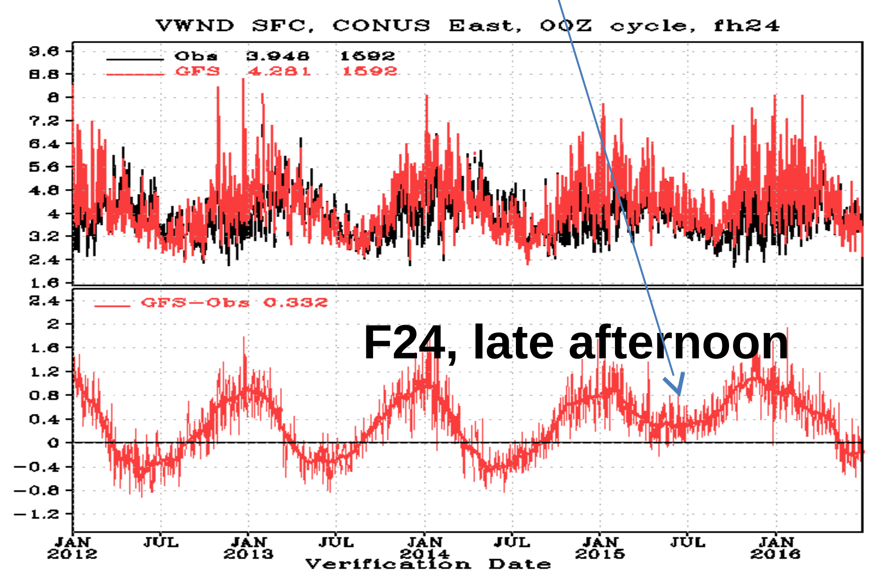




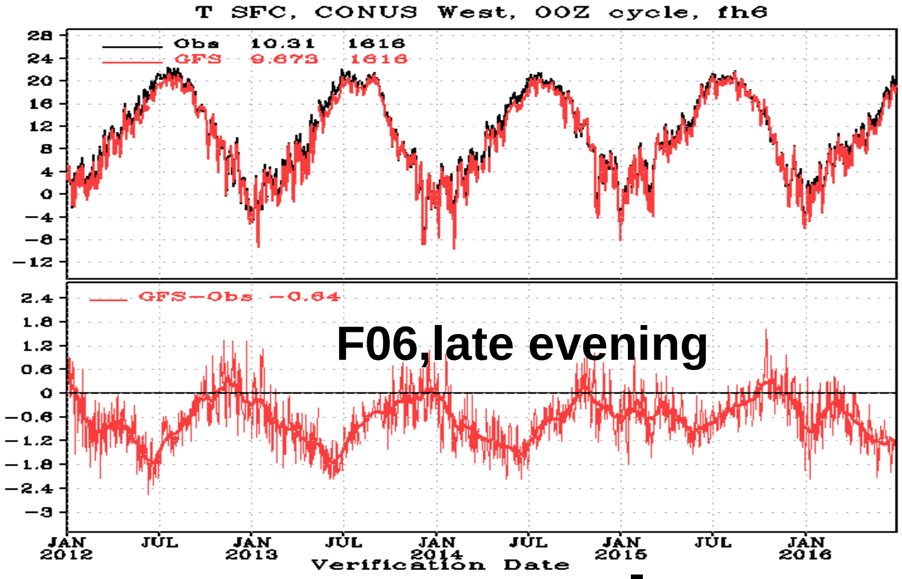
T574 Eulerian | ***T1534 SLG***

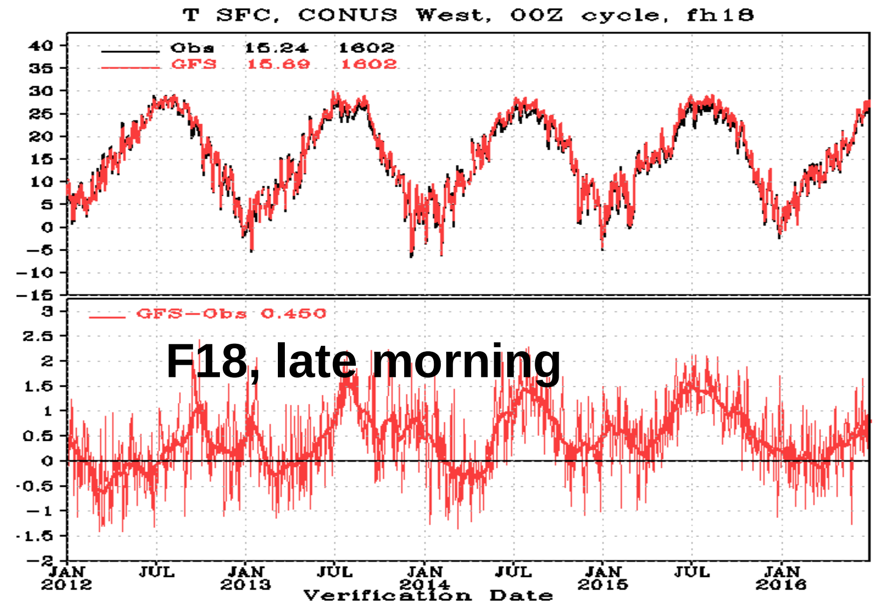
Wind stronger in JJA 2015



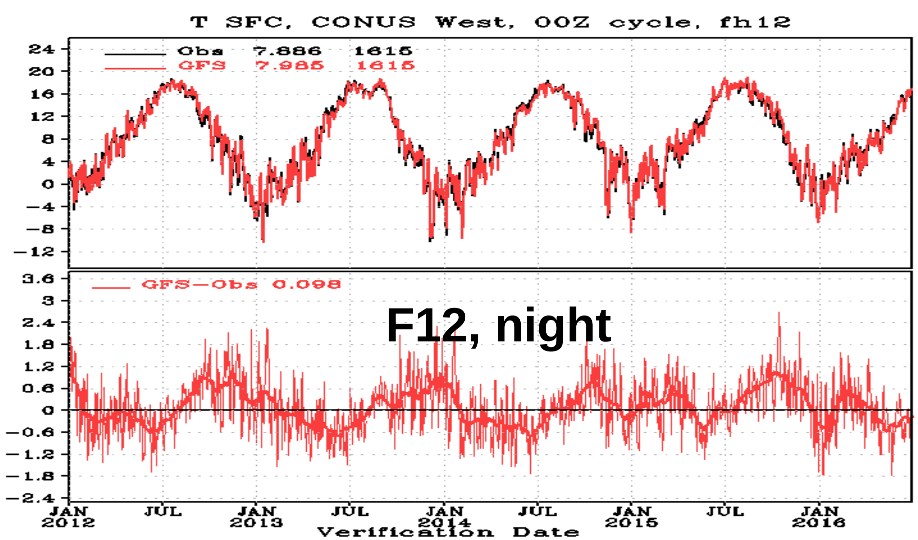


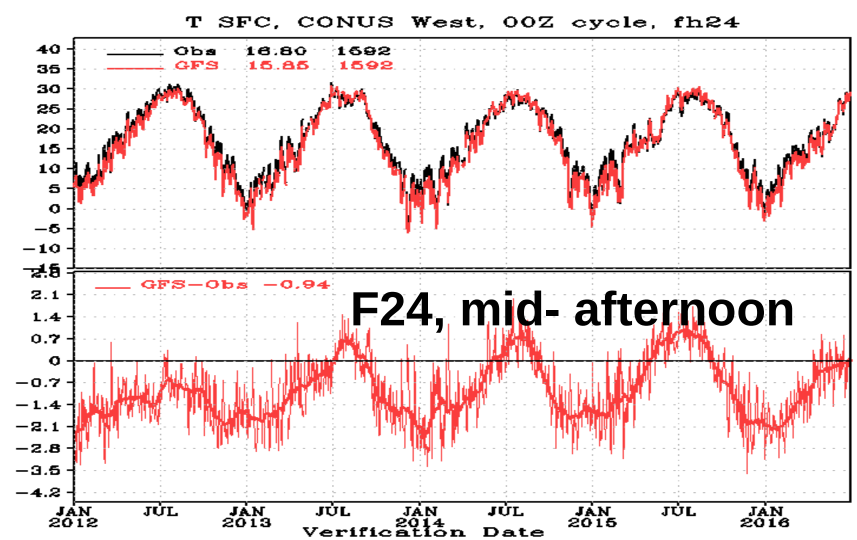
T2m over CONUS West, Jan2012 ~ Jun2016



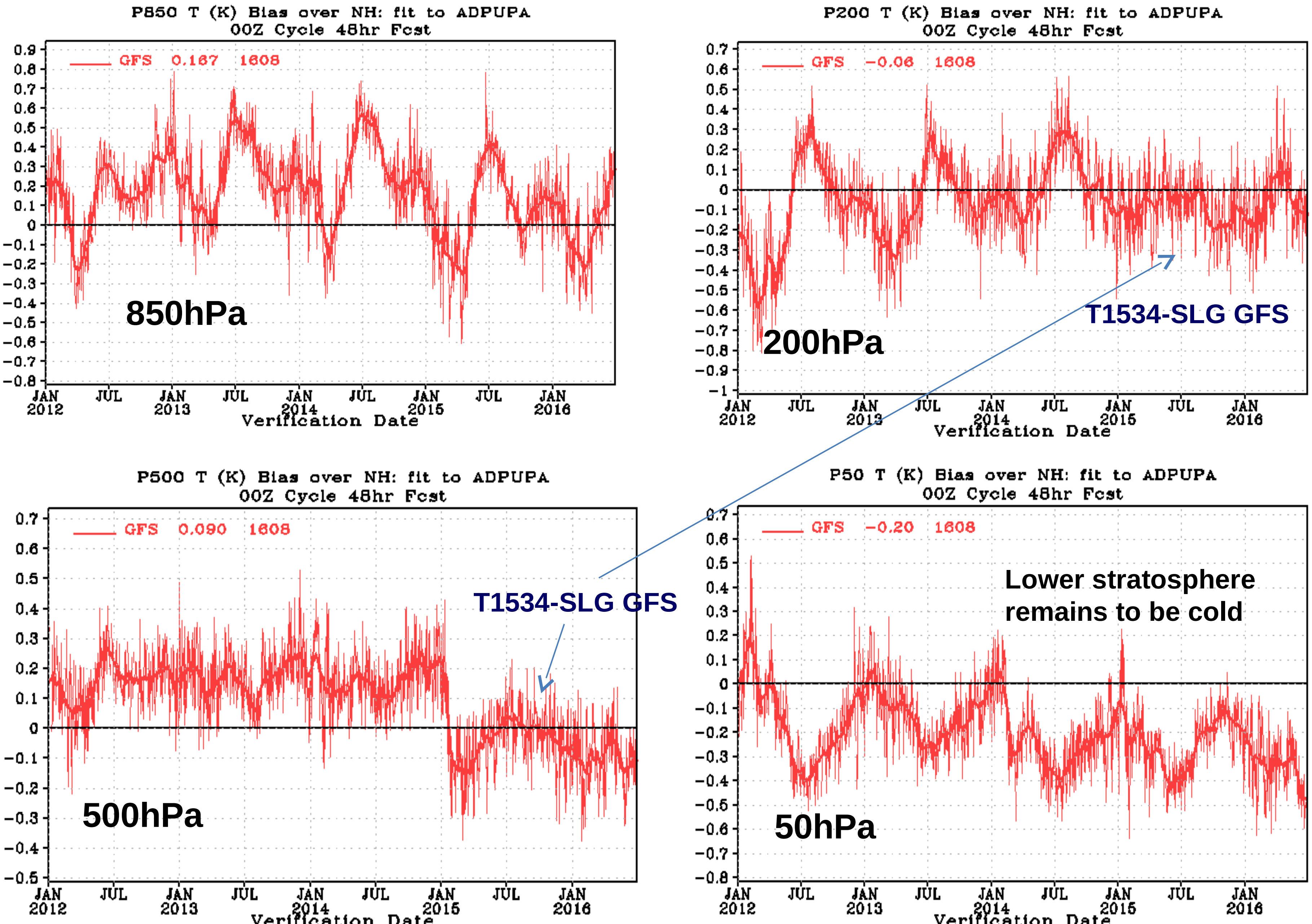


T574 Eulerian | *T1534 SLG*

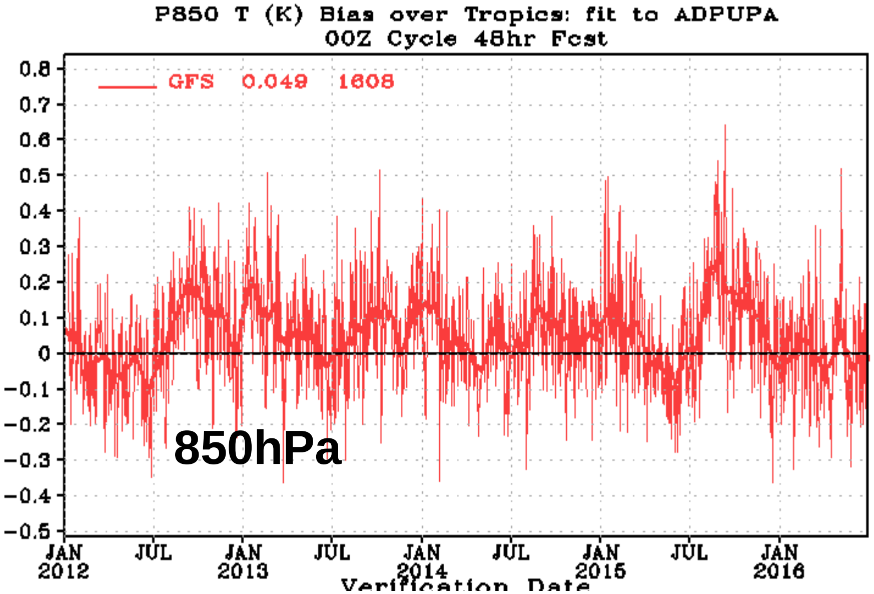


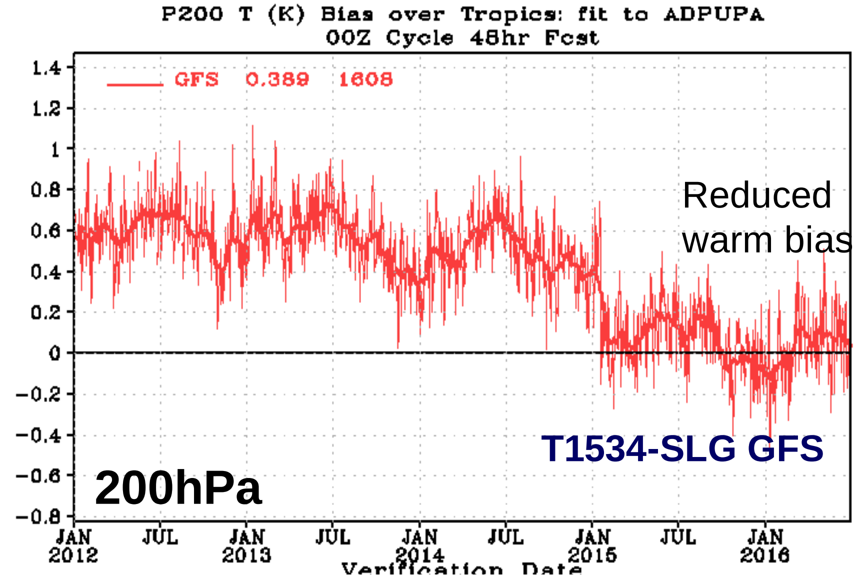


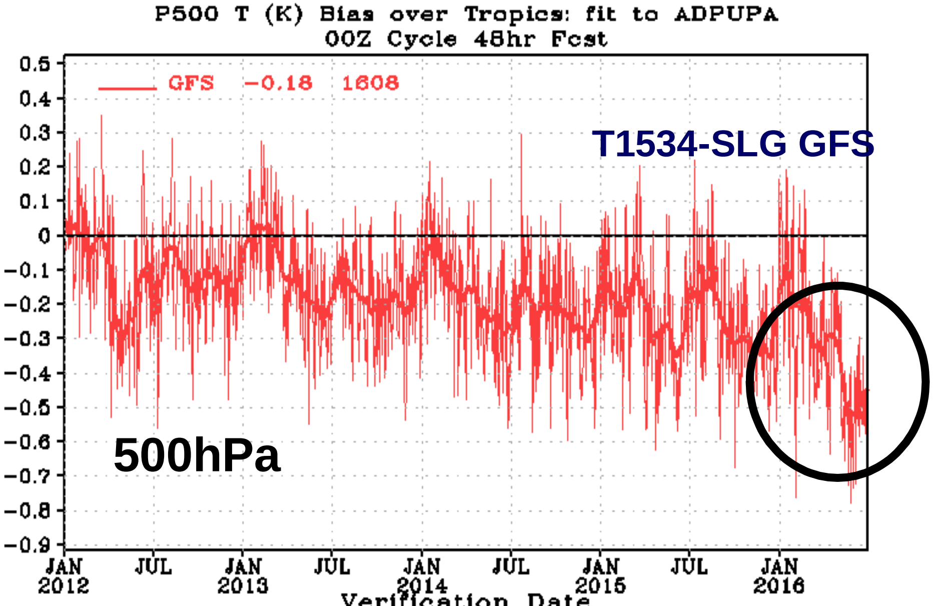
48-Fcst, NH Temperature Fit to RAOBS, Jan2012 ~ Jun2016

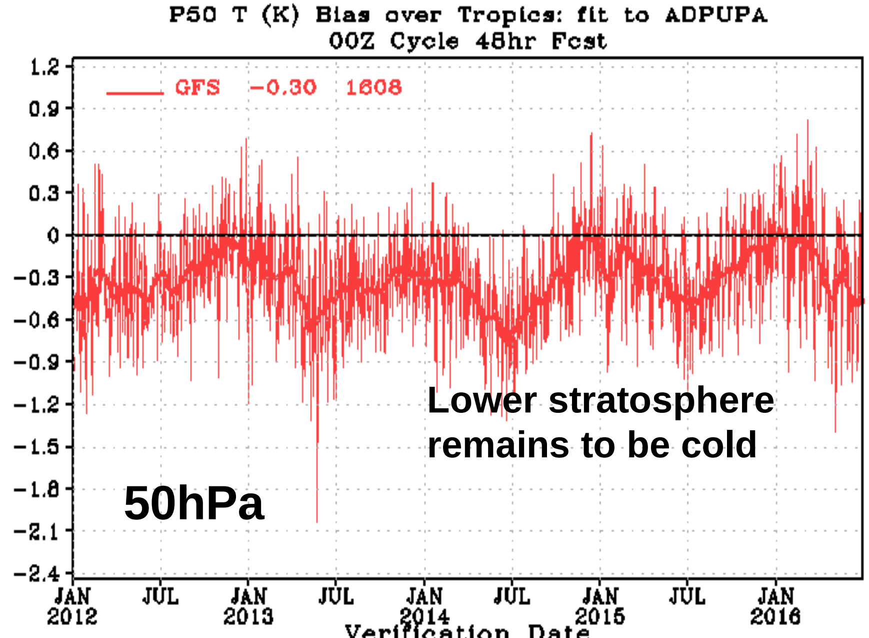


48-Fcst, Tropical Temperature Fit to RAOBS, Jan2012 ~ Jun2016

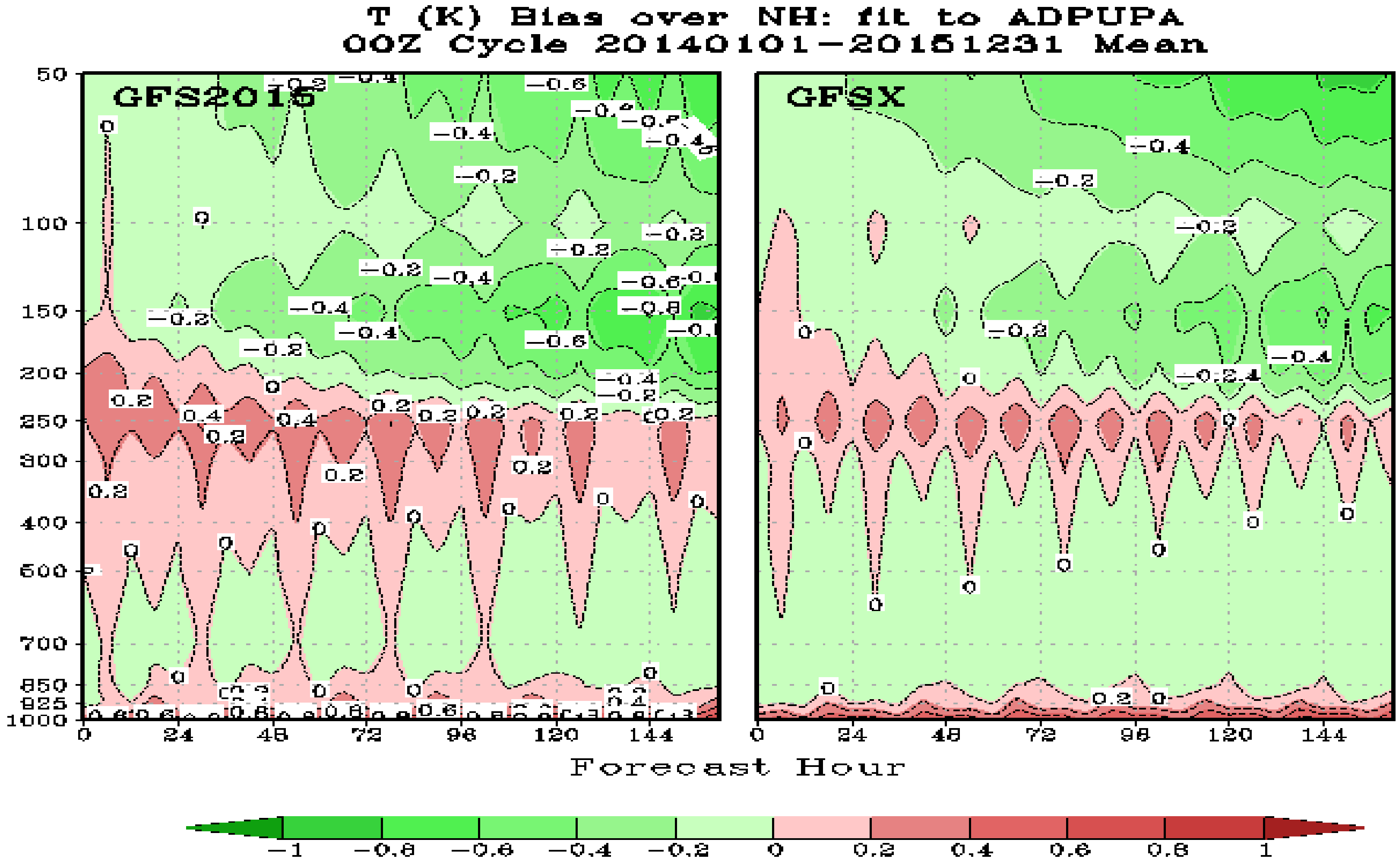








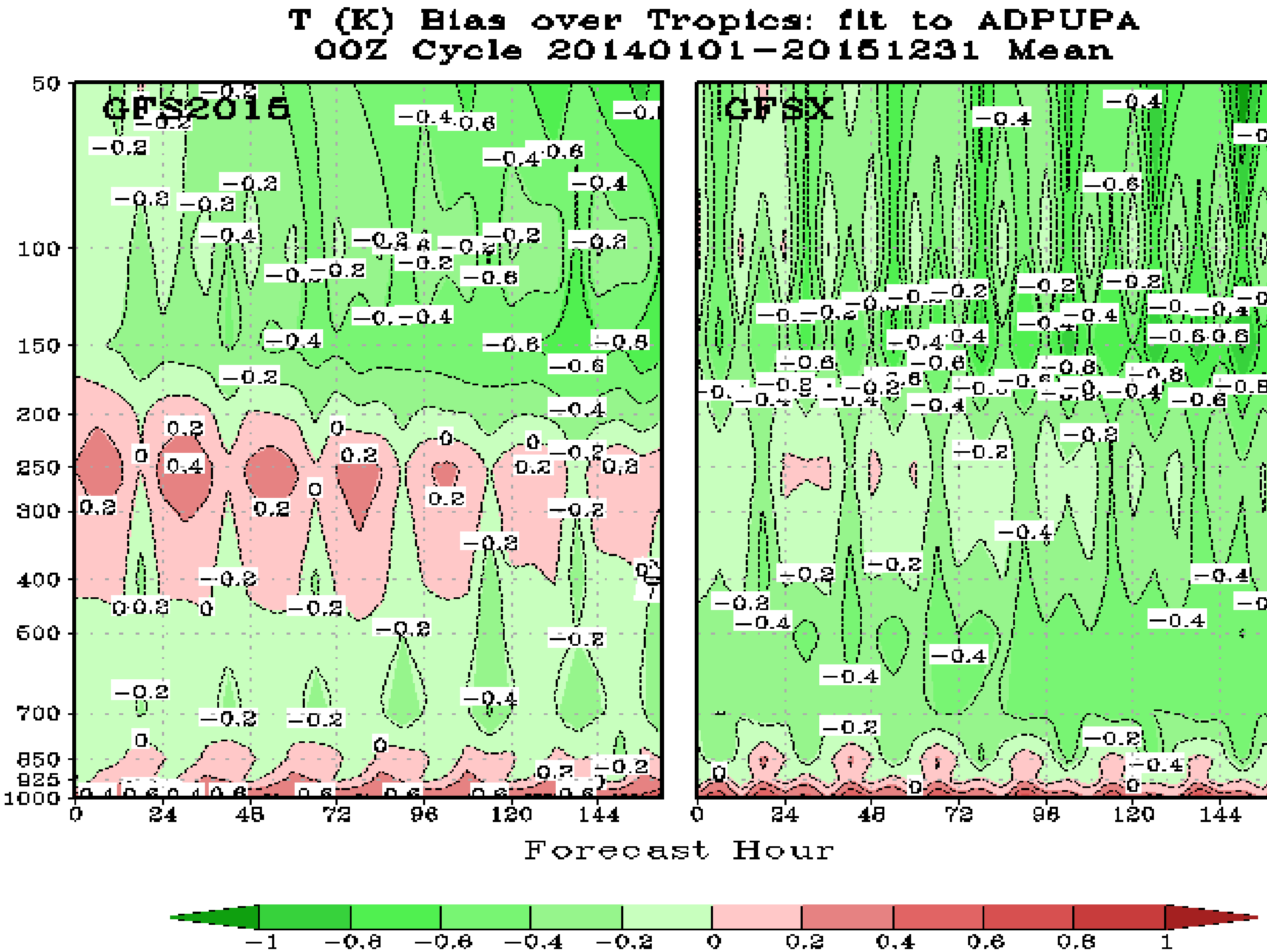
NH Temperature Bias, Verified against Rawinsonde Observations



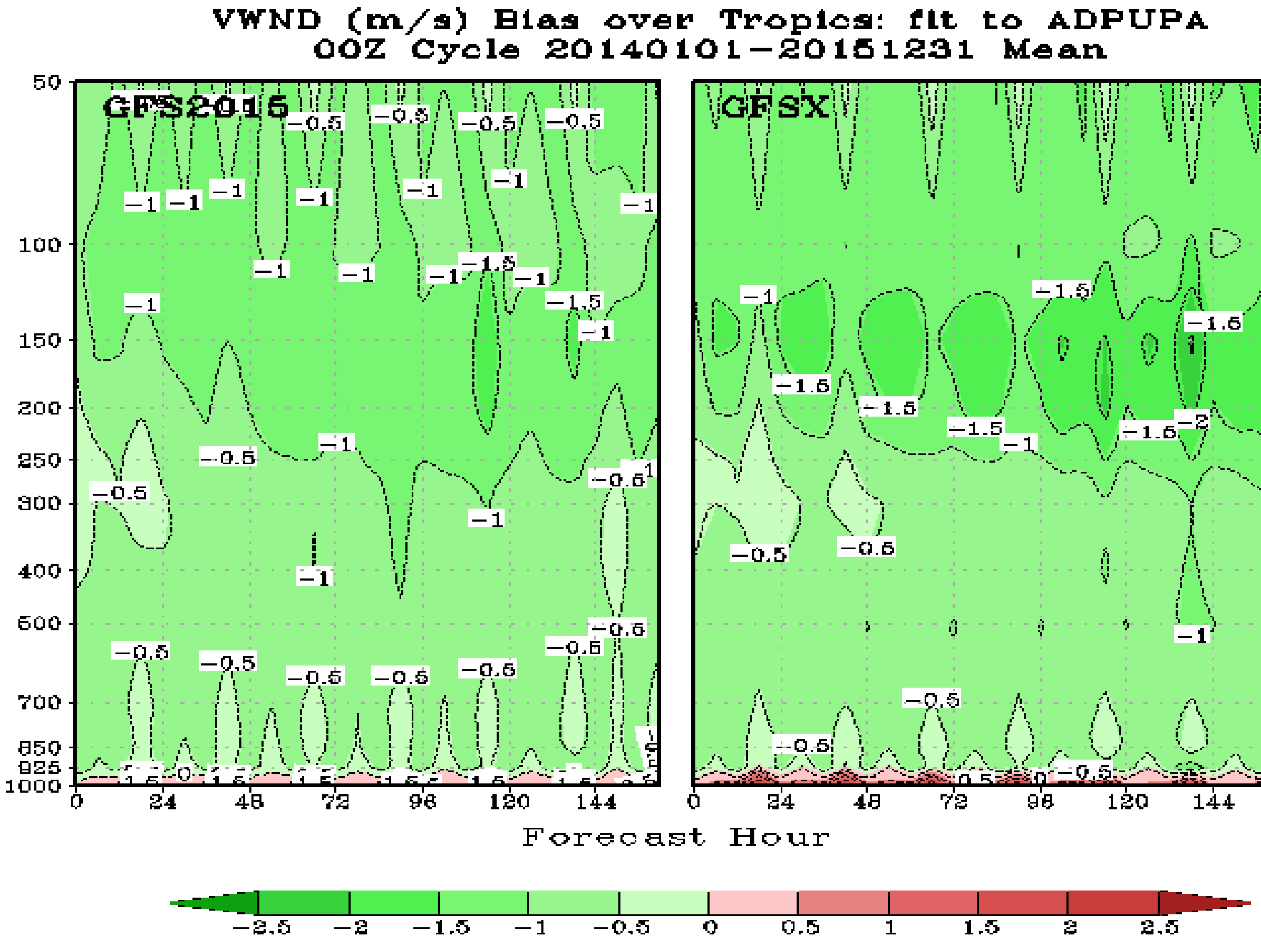
2015 Operational Model

Current operational Model

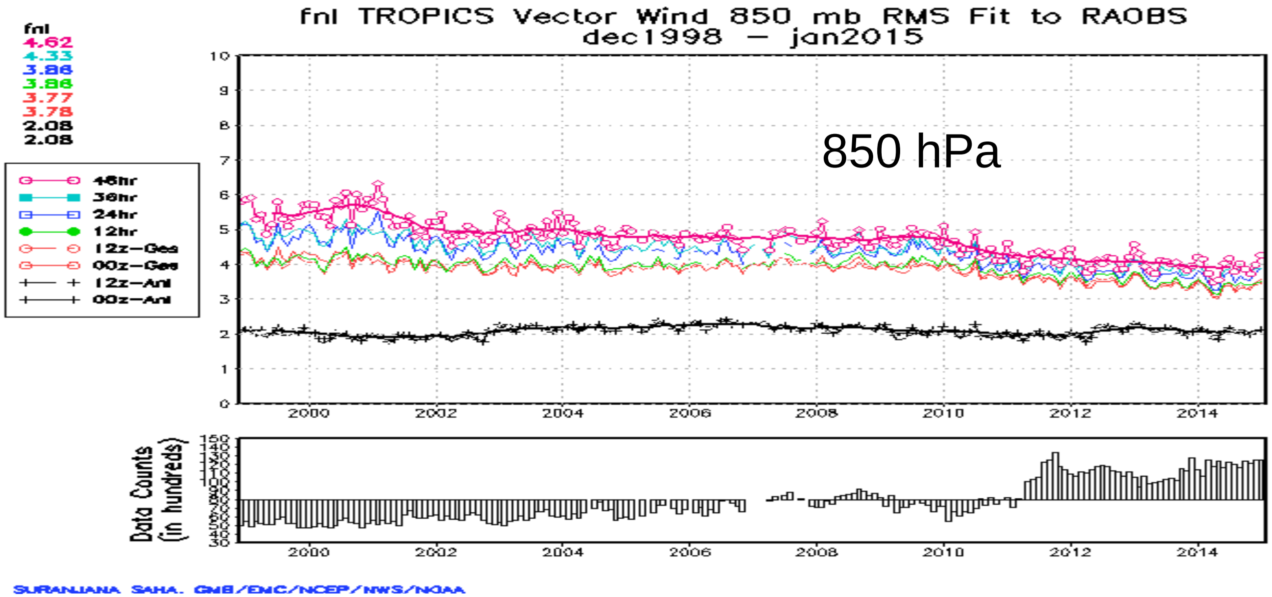
Tropical Temperature Bias, Verified against Rawinsonde Observations

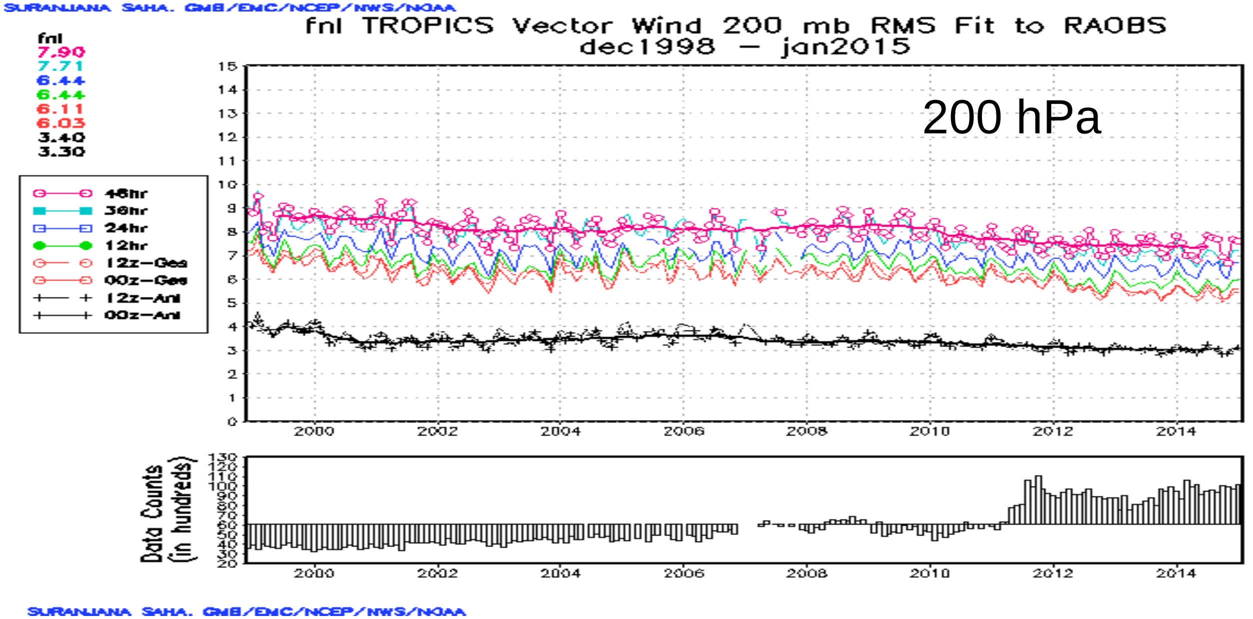


Tropical Wind Bias,   Verified against Rawinsonde Observations



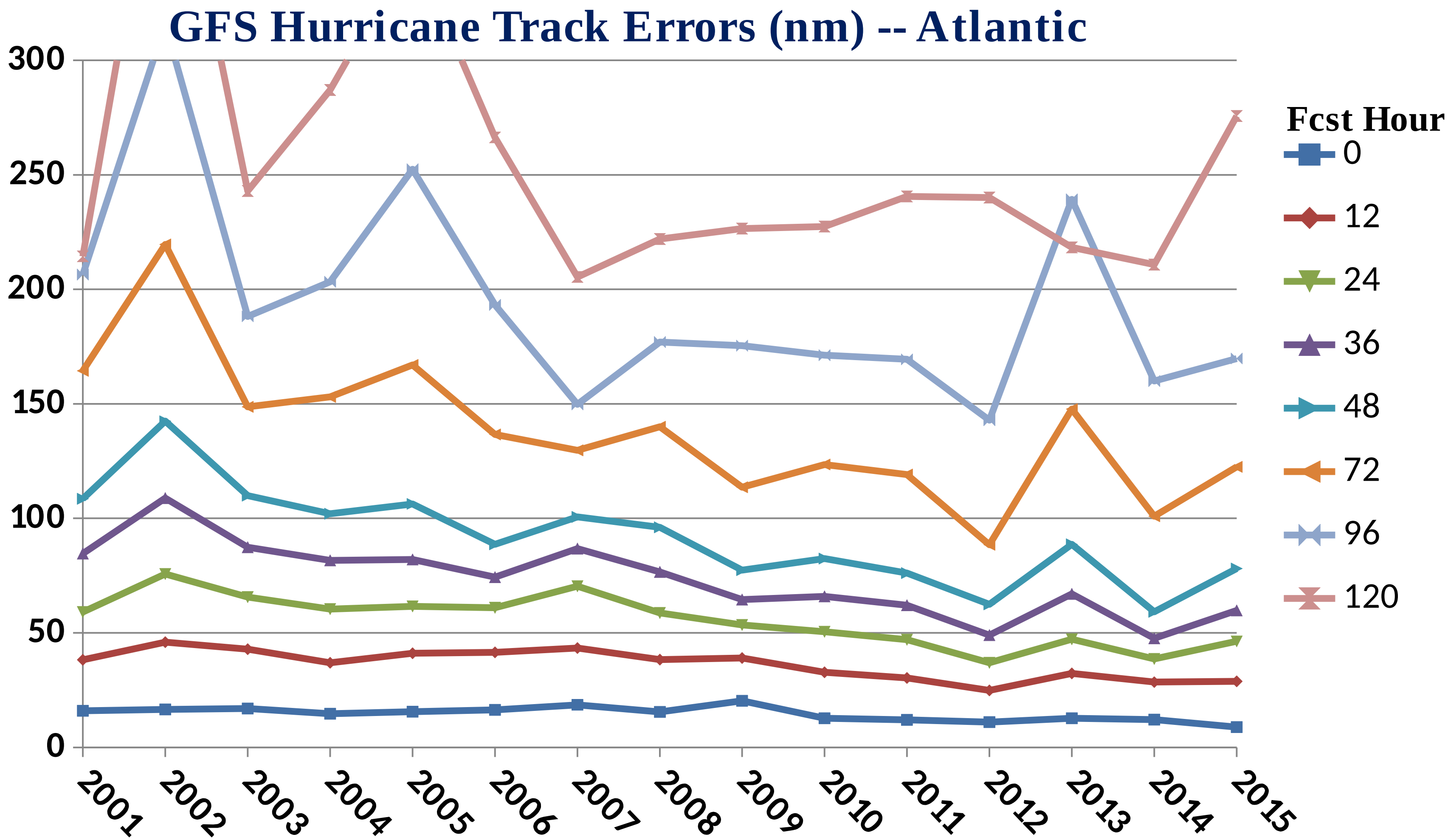
Long-Term Fit-to-Obs : Tropical Wind, 1998-2014
Credit: Suru Saha



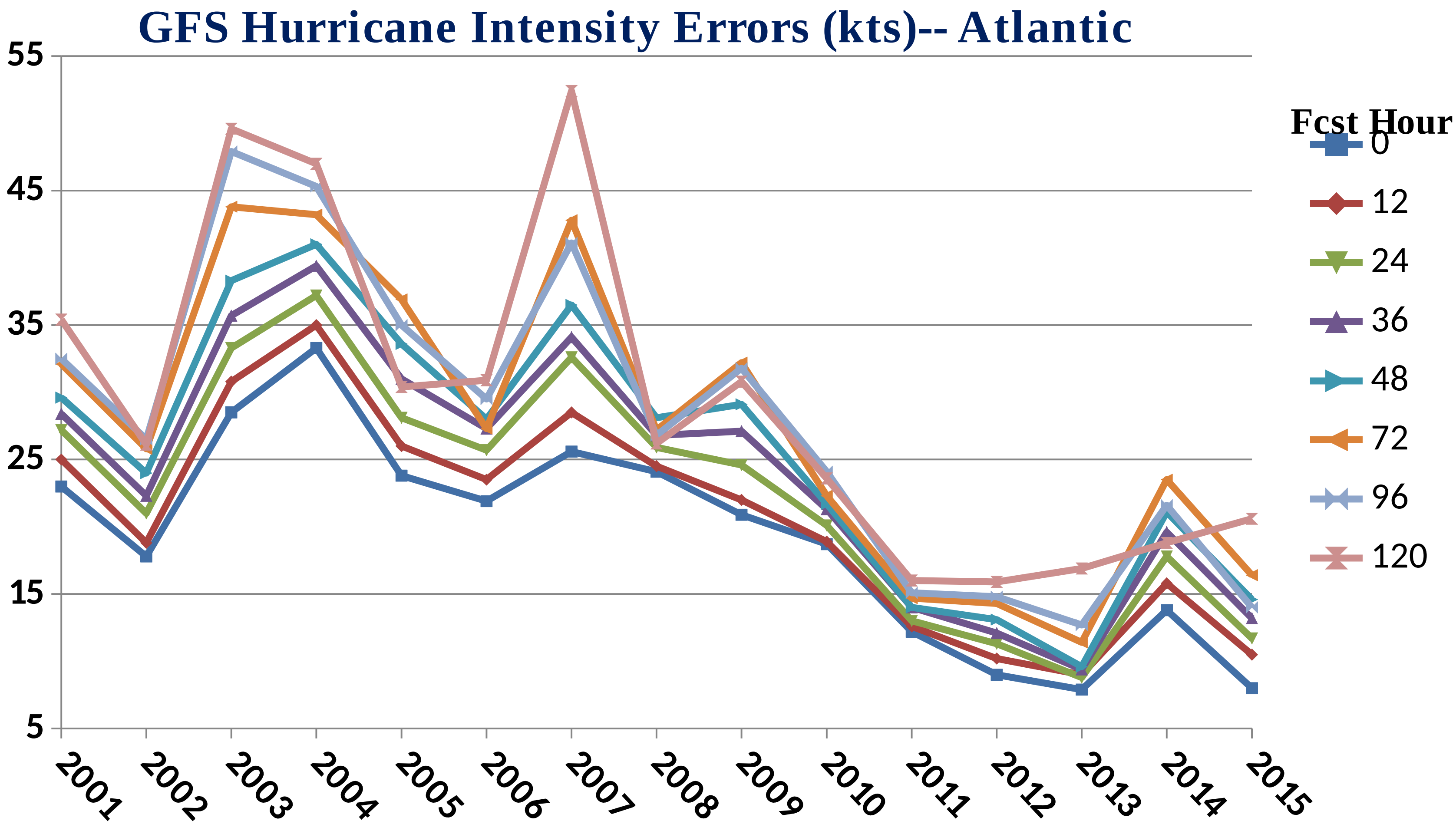


- **RMSE of predicted tropical wind has been gradually reduced from year to year.**
- **The improvement after 2010 T574 implementation was the largest.**
- **RMSE of analyses was reduced by 1.0 m/s from 1998 to 2014 at 200 hPa, but showed little change at 850hPa.**

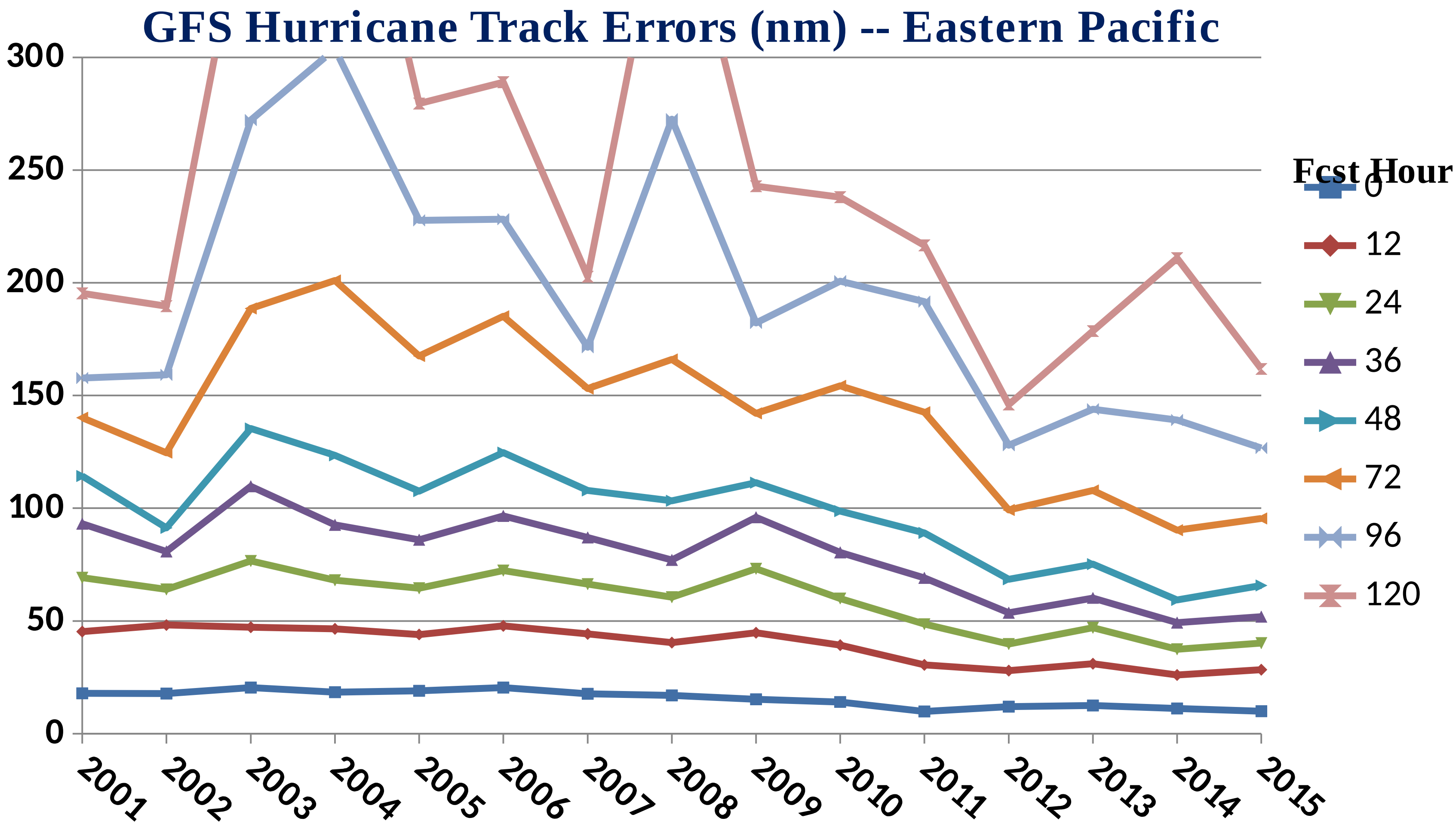
Hurricane Track and Intensity



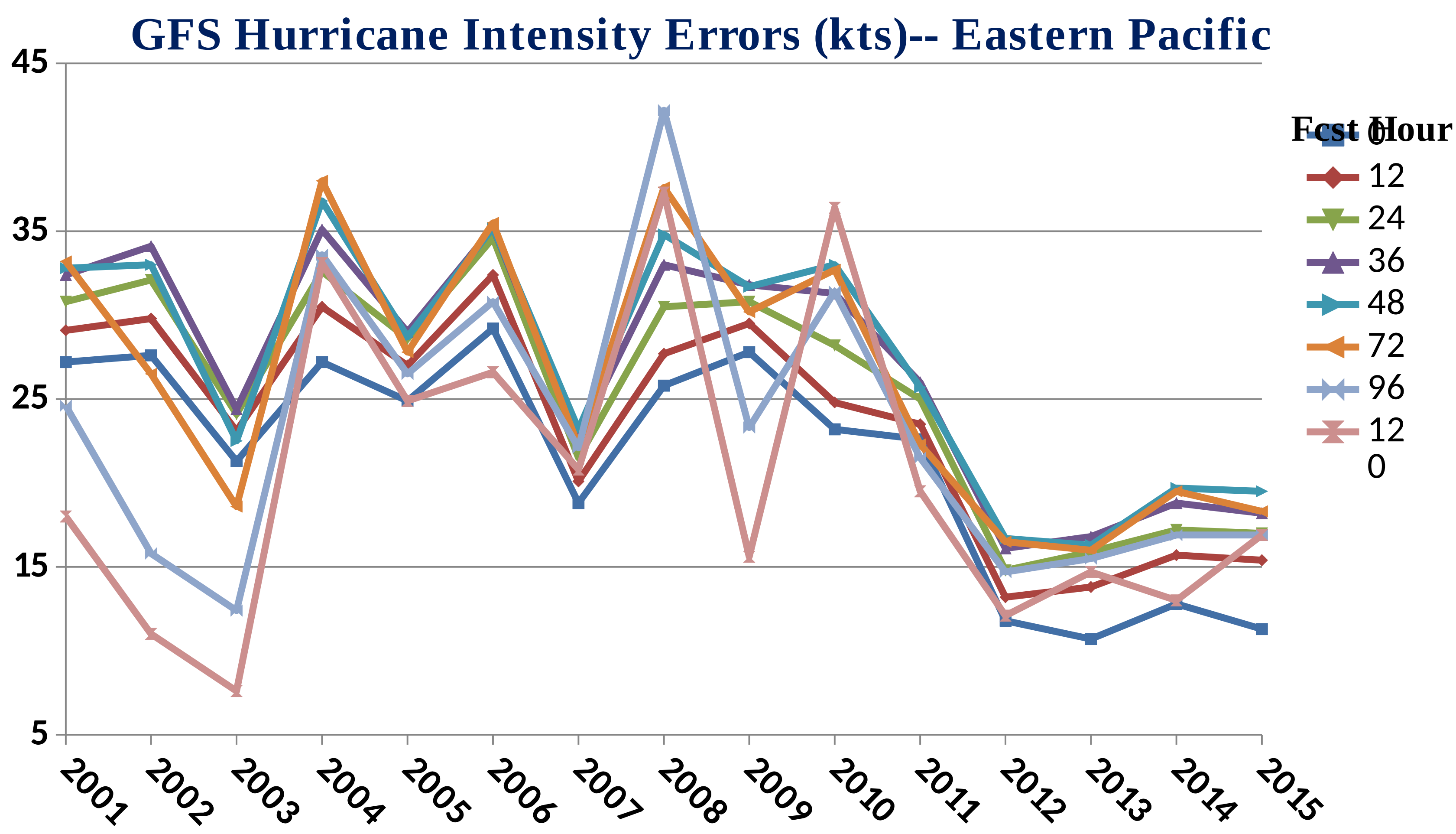
- **Track for all forecast leading time has been improved in the past 15 years; 72-hr track error reduced from 200nm to ~100nm**



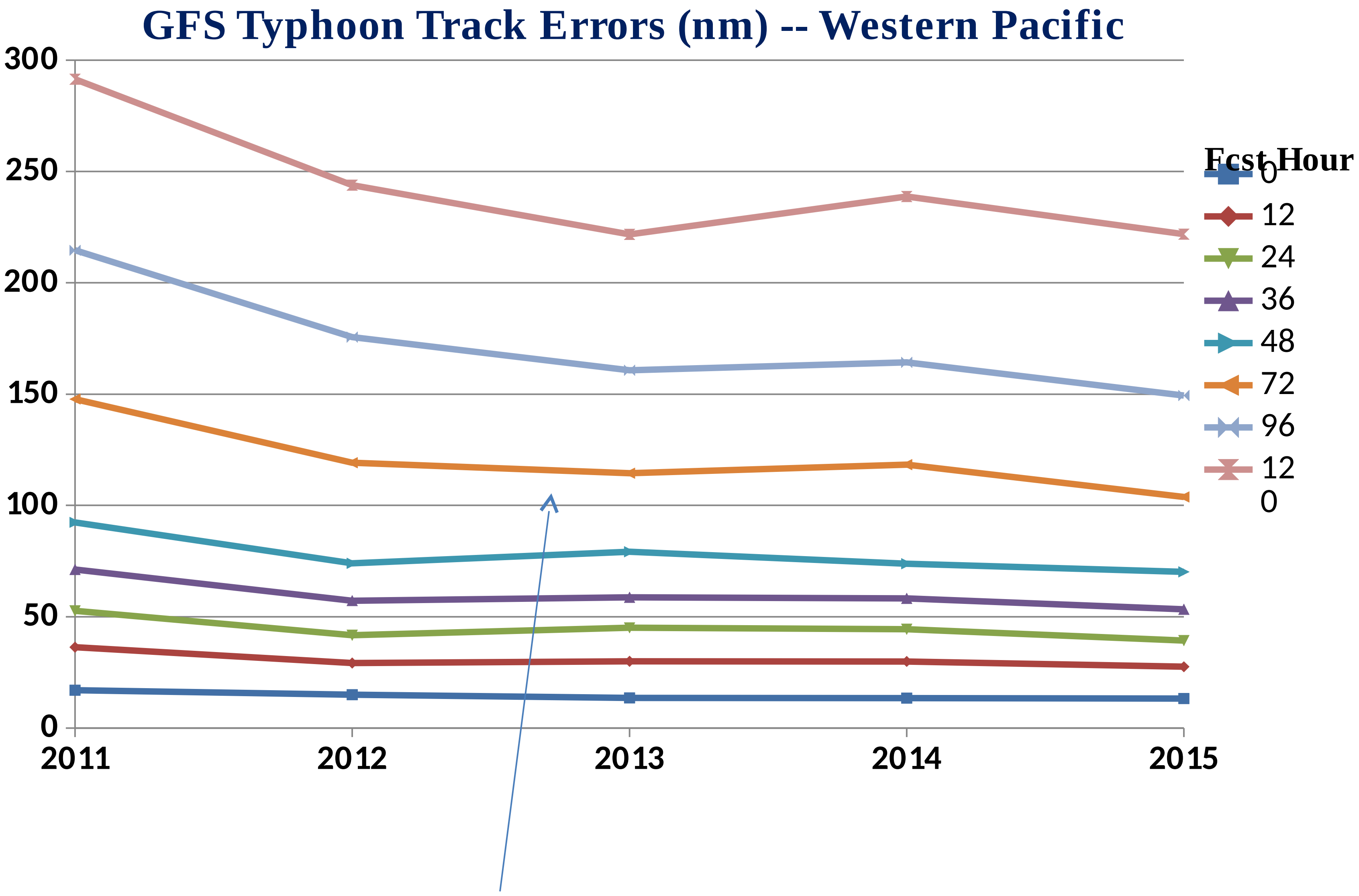
- Intensity improved in 2010 and 2011 due to GFS resolution increase from 35km to 23km and major physics upgrade;
- in 2012 and 2013 due to ENKF-3DVAR GSI Implementation in May 2012;
- in 2015 due to T1534 SLG GFS (~13km) implementation.
- 2014 was a difficult year to forecast



Significant track error reduction in the past 15 years. 36-hr track error reduced from 100nm to 50nm; 72-hr track reduced from 200 nm in 2004 to 100 nm in 2015 .

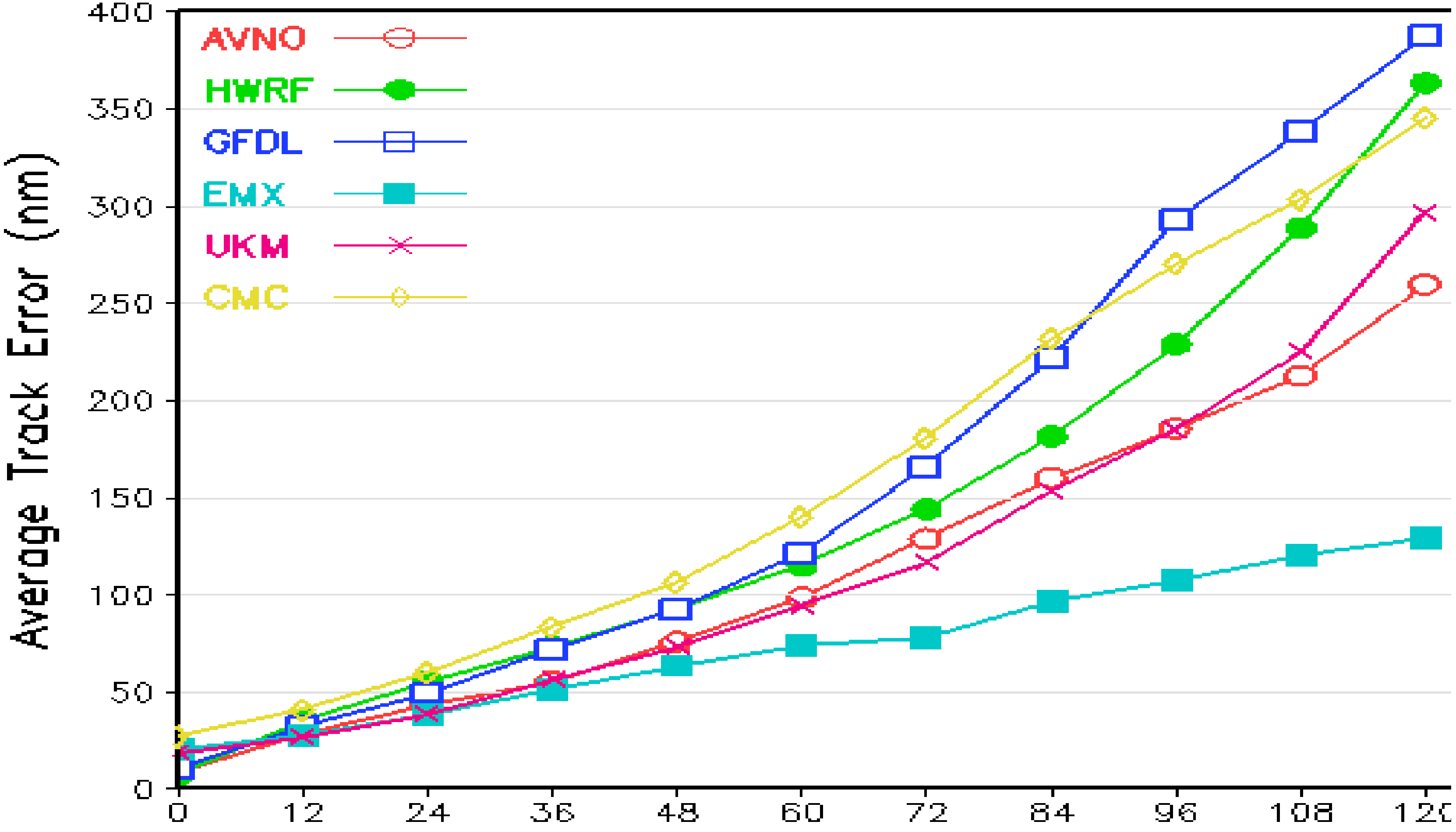


Large reduction after 2010 T574 GFS Implementation. No changes in past few years.



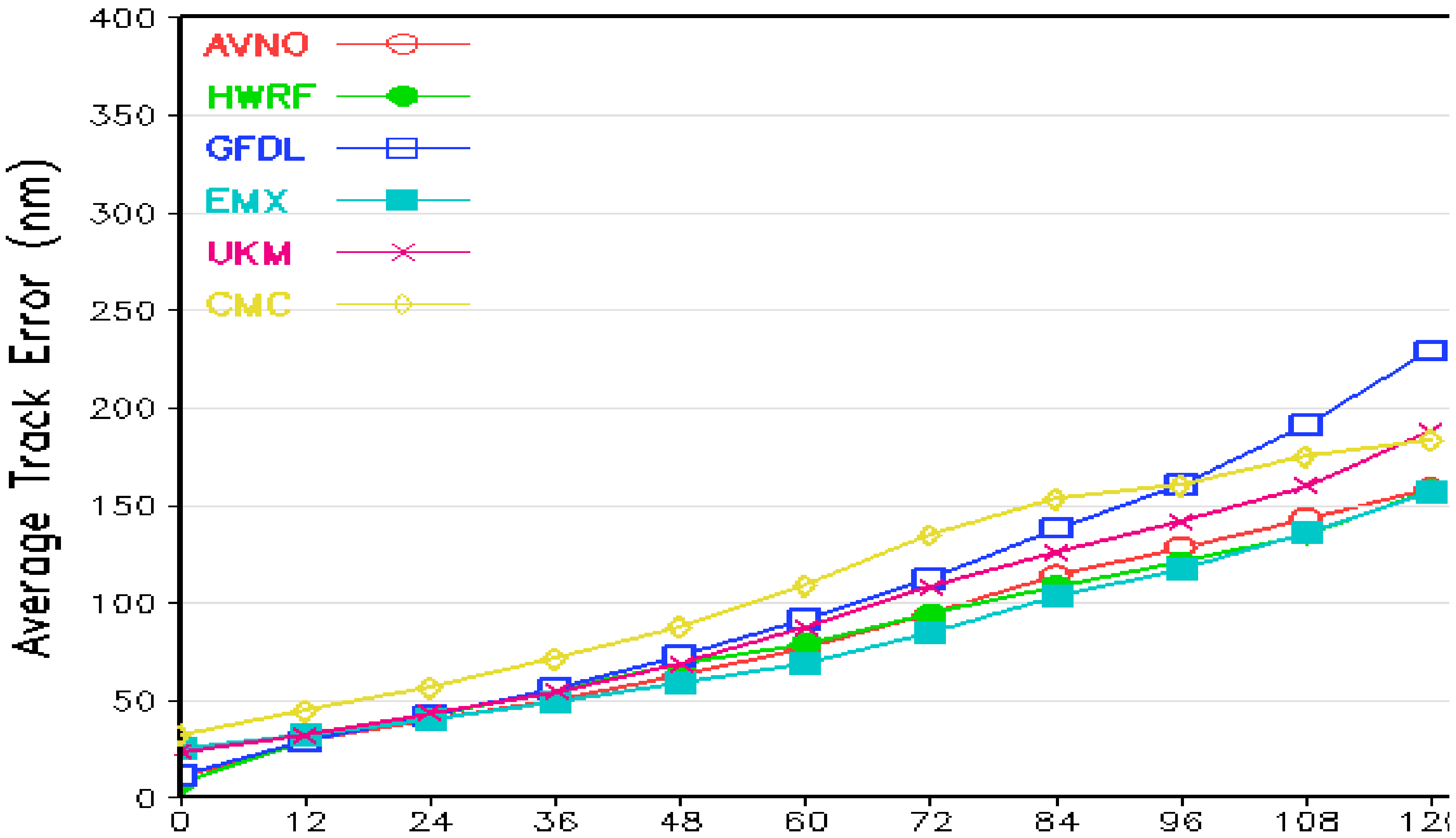
72-hr forecast error reduced from 150 to 100 nm in 5 years.

2015 Atlantic – Track Errors (00Z and 12Z Cycles)



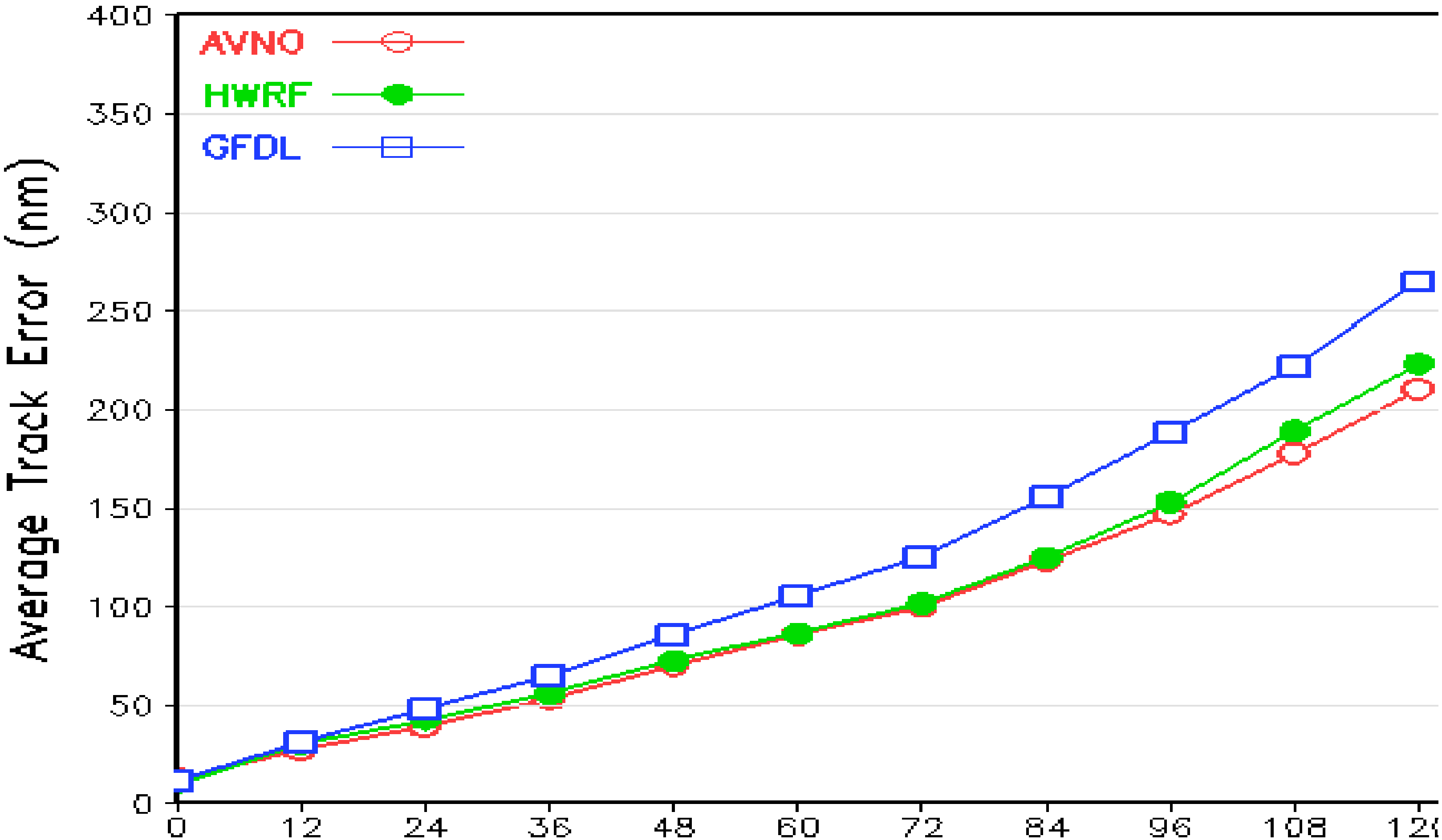
GFS (AVNO) tied with UKM; ECMWF had the best skill.

2015 Eastern Pacific – Track Errors (00Z and 12Z Cycles)



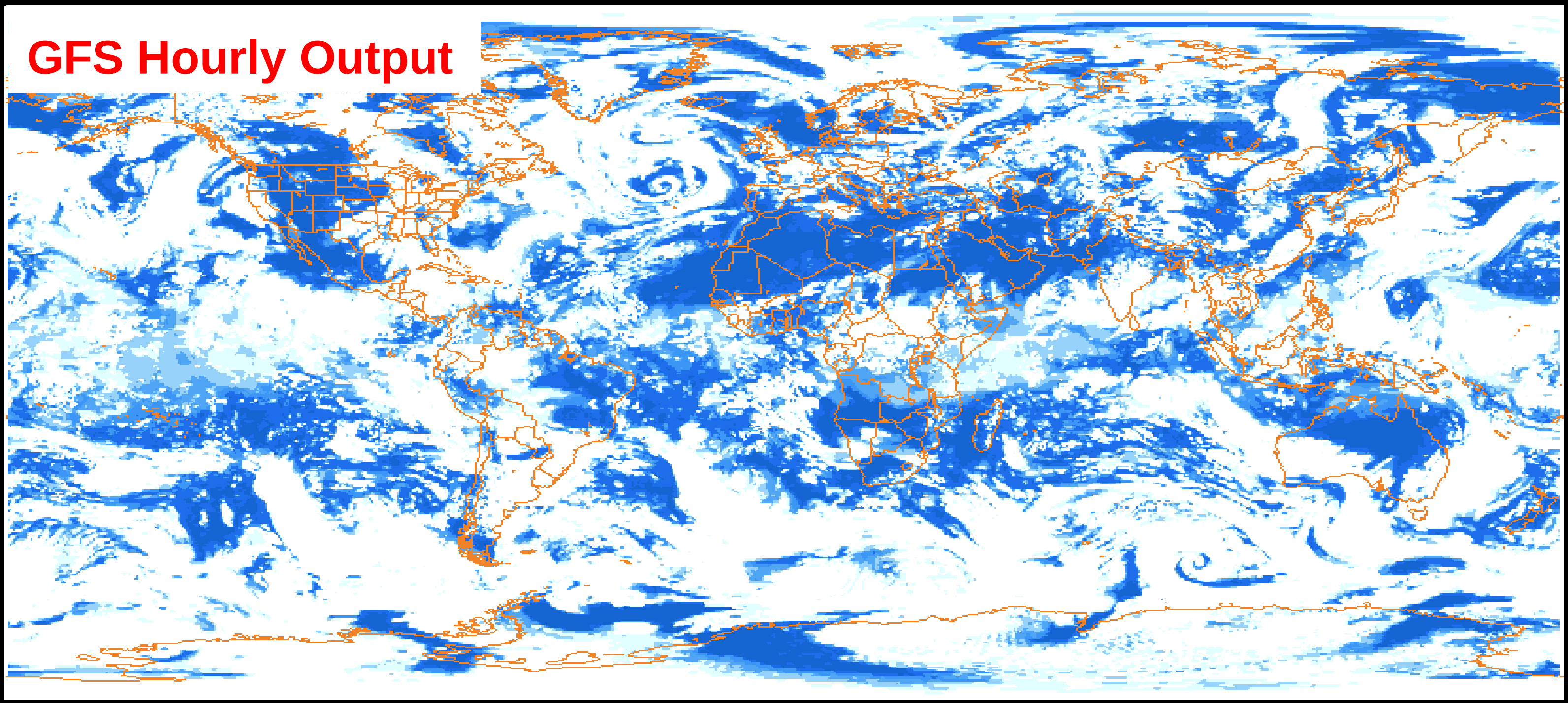
GFS (AVNO), HWRF and ECMWF had similar skills.

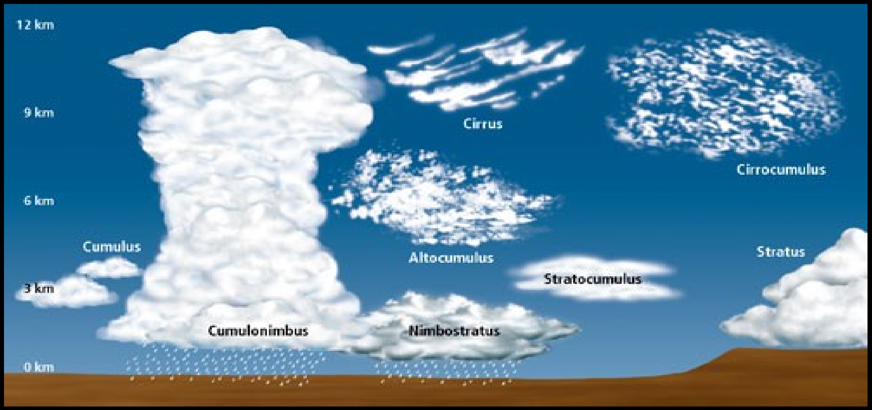
2015 Wesatern Pacific – Track Errors (00Z and 12Z Cycles)



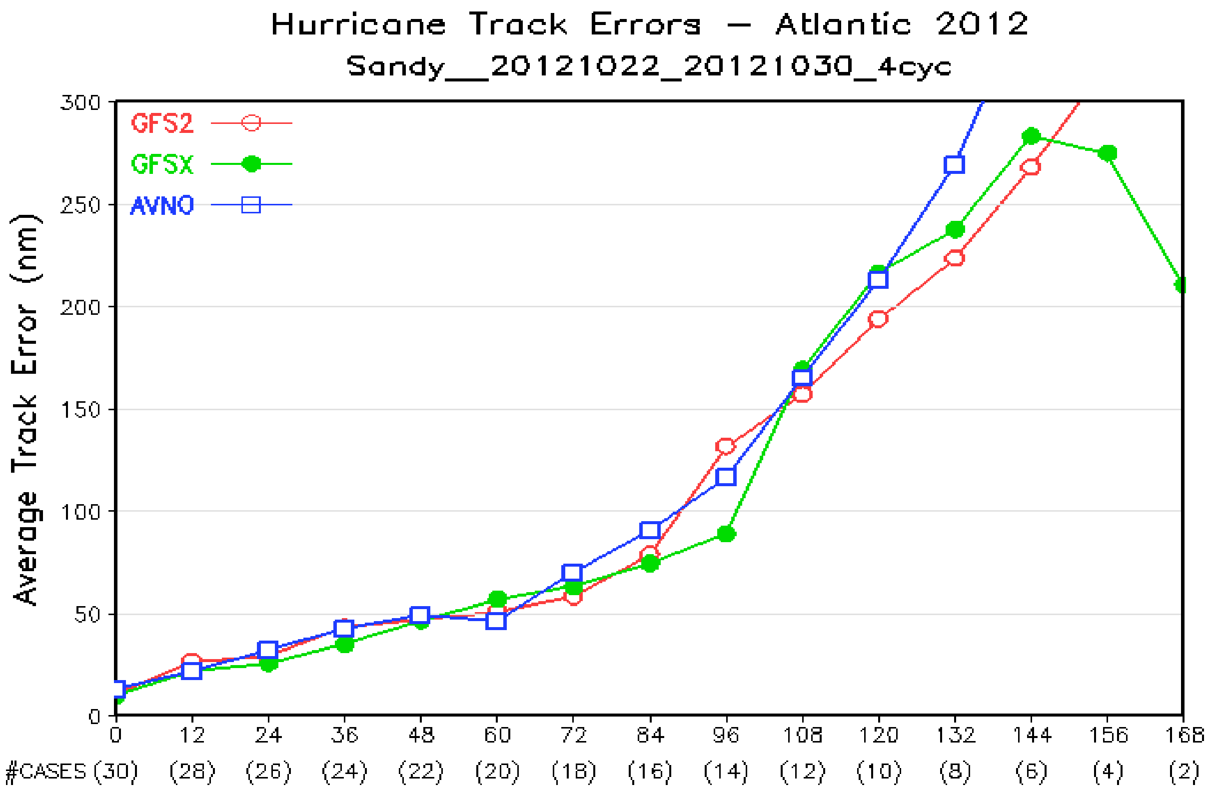
GFS (AVNO) and HWRF had similar skills.

20160604 t12z Forecast for 2016060413 (f001)
GFS Cloud Cover, 0.25x0.25-deg





Hurricane Sandy

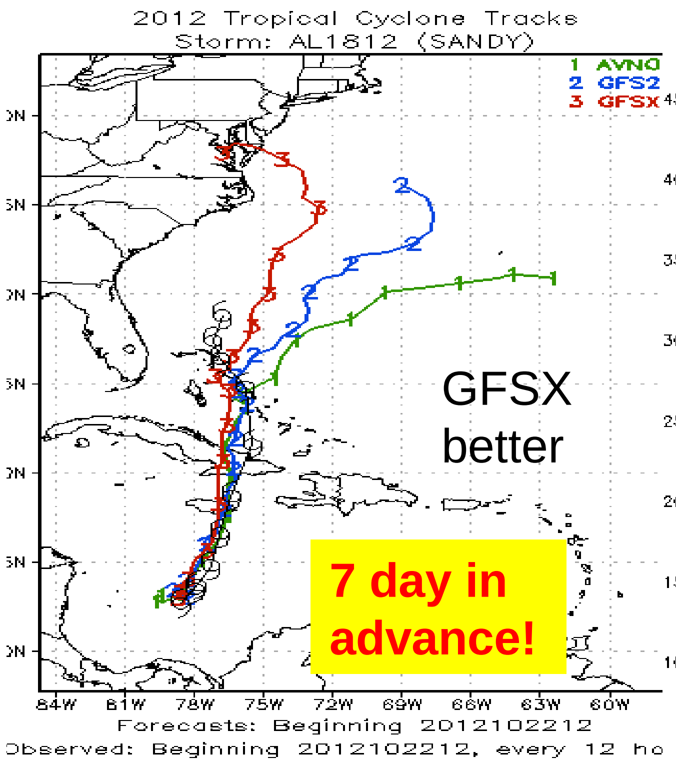


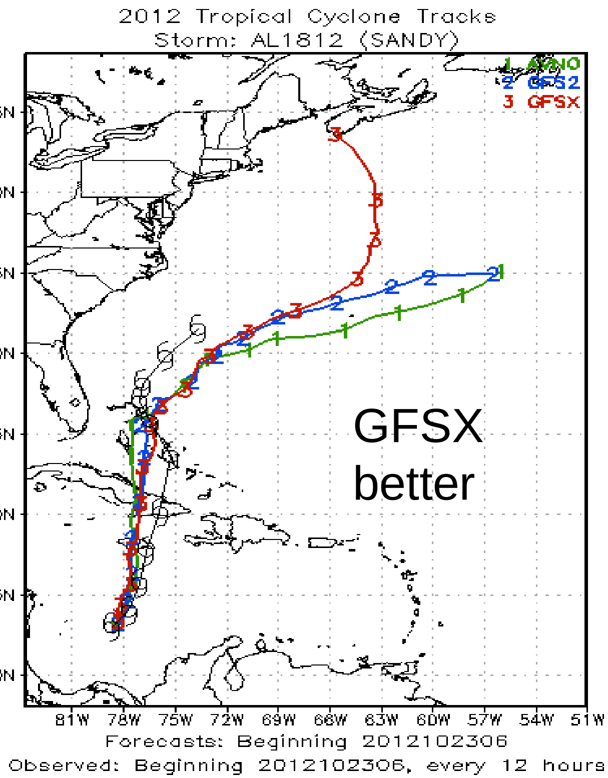
Confidence Level (%) of Student-t Tests

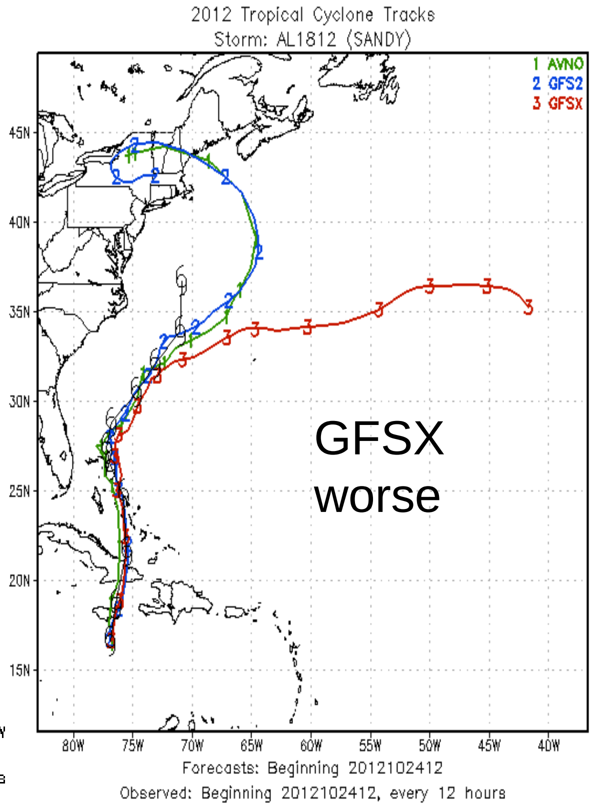
GFS2_GFSX	82	95	89	97	53	84	72	66	97	70	80	63	78	90	99
GFS2_AVNO	84	94	74	53	67	72	81	80	91	64	76	84	99	99	99
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

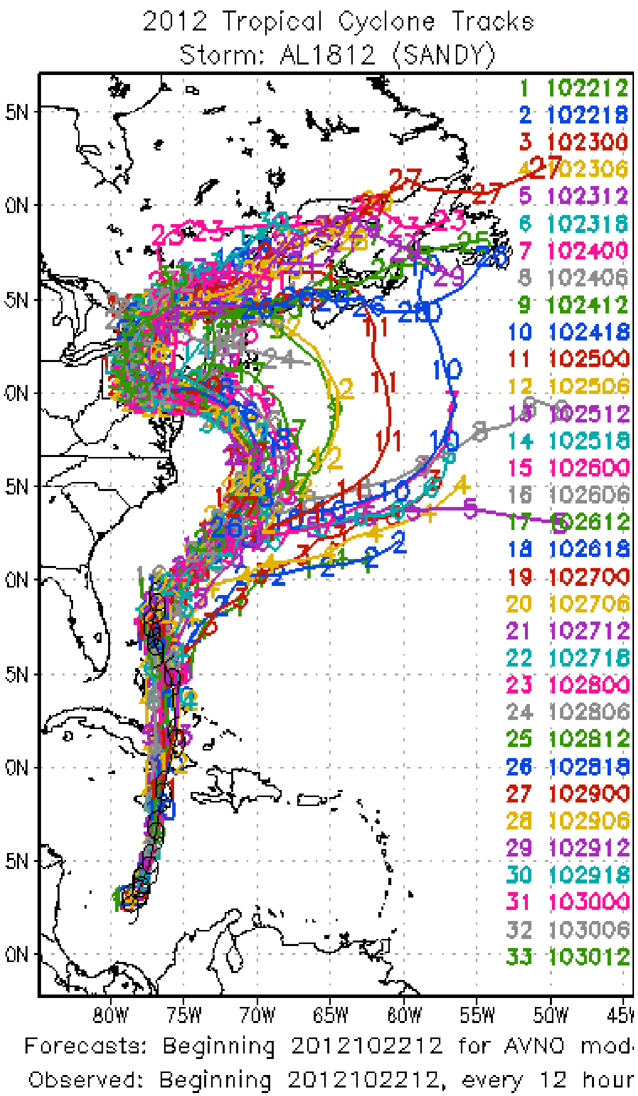
GFS2: T1534 GFS implemented in January 2015 (3D En-Var)
GFSX: T1534 GFS to be implemented in May 2016 (4D En-Var)
AVNO: 2012 operational GFS (T574 Eulerian GFS, 3D En-Var, ~23km)

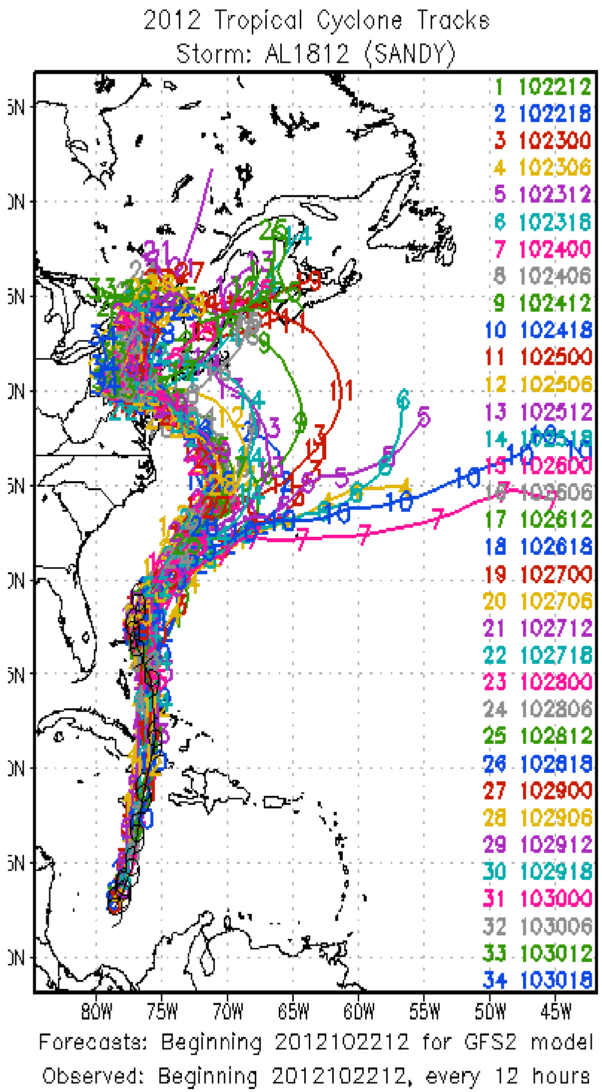
- Mean track indicates GFSX has much a better forecast than AVNO and GFS2015 at the 7-day lead time, evidently showing in the 2012102212 individual track plot. GFSX also did well for the cycle 2012102306 case. Other than that, it appears GFSX's performance is similar to GFS2015. One case (2012102412) showed GFSX is worse than AVNO and GFS2015.

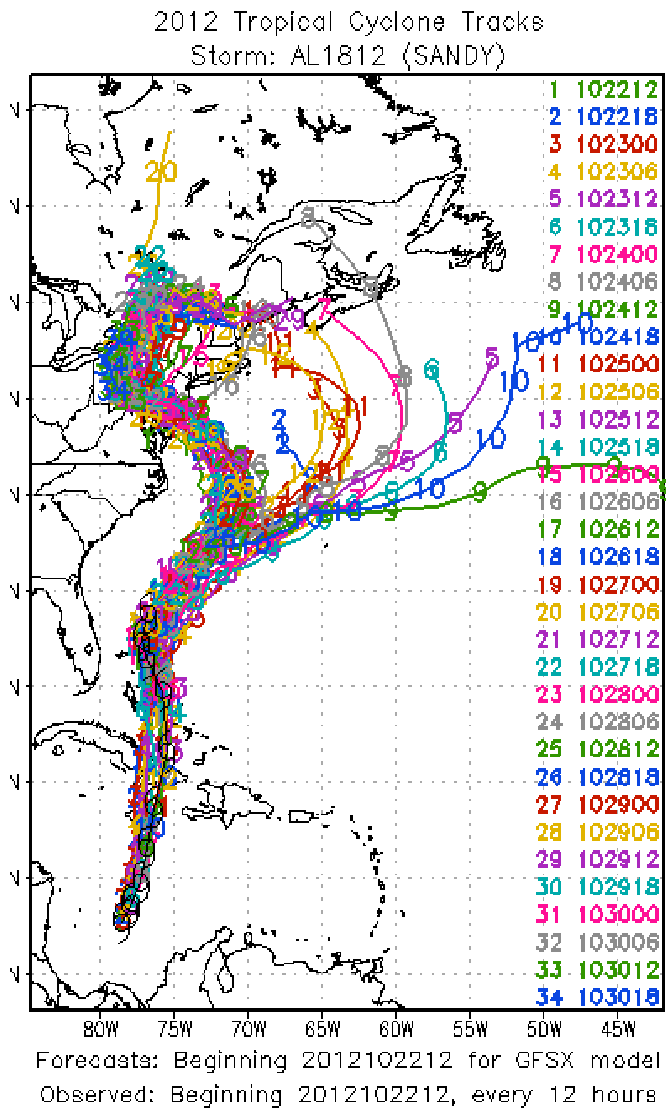












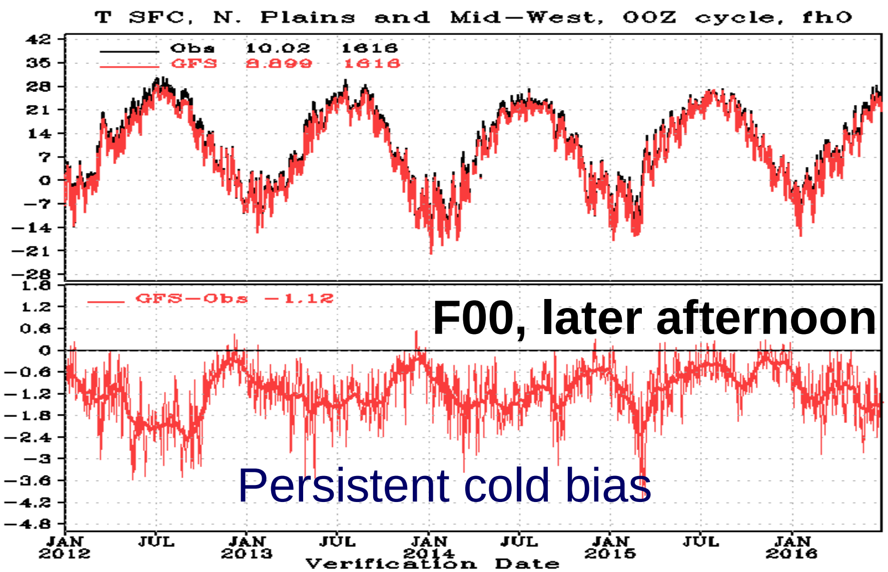
2012 Operational GFS

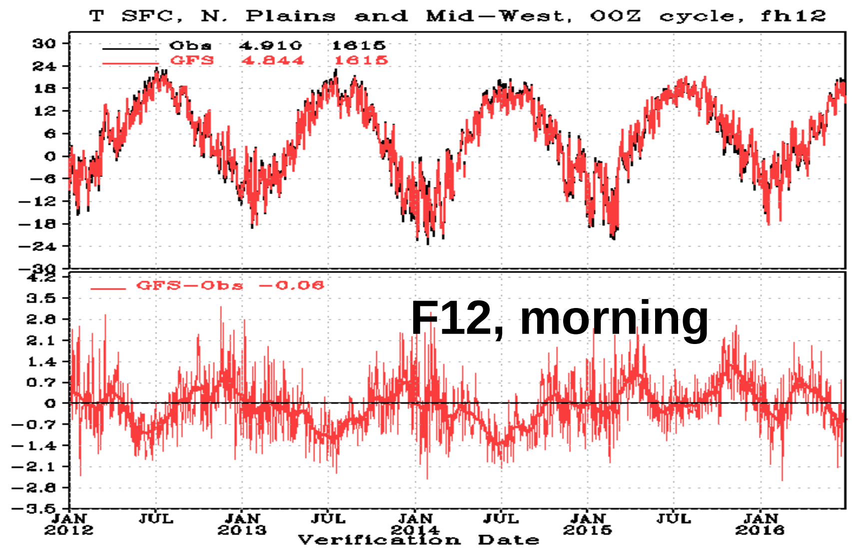
Current Operational SL-GFS

GFSX

GFSX has slightly better cycle-to-cycle forecast consistency

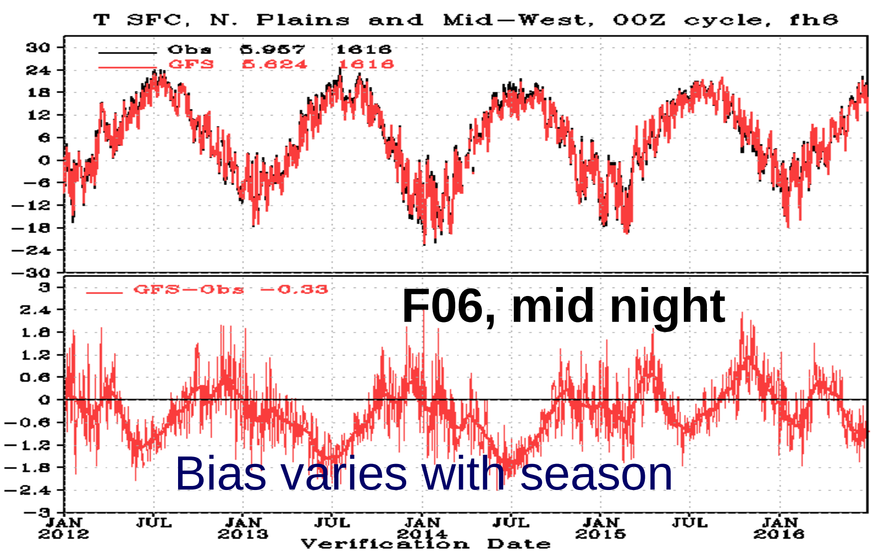
T2m over Northern Great Plains, Jan2012 ~ Jun2016

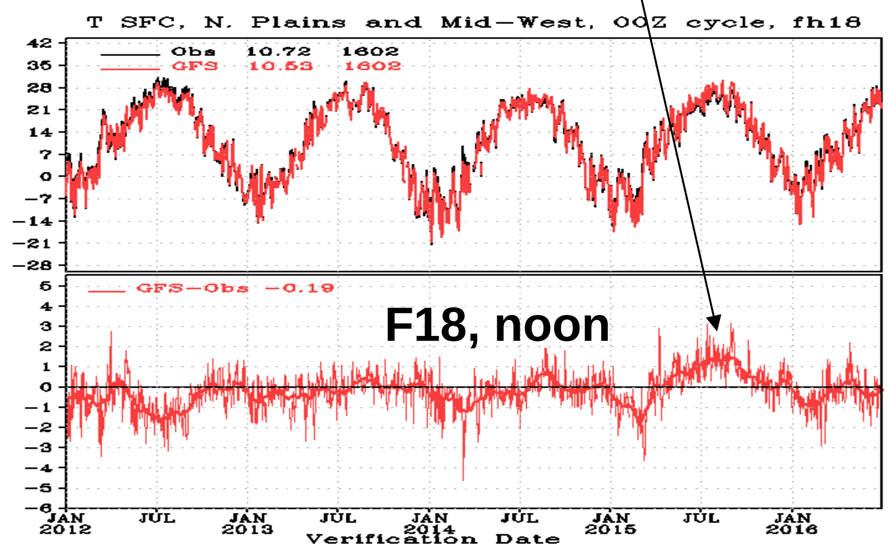




T574 Eulerian ***T1534 SLG***

2015 summer warm bias





T2m over US Northeast, Jan2012 ~ Jun2016